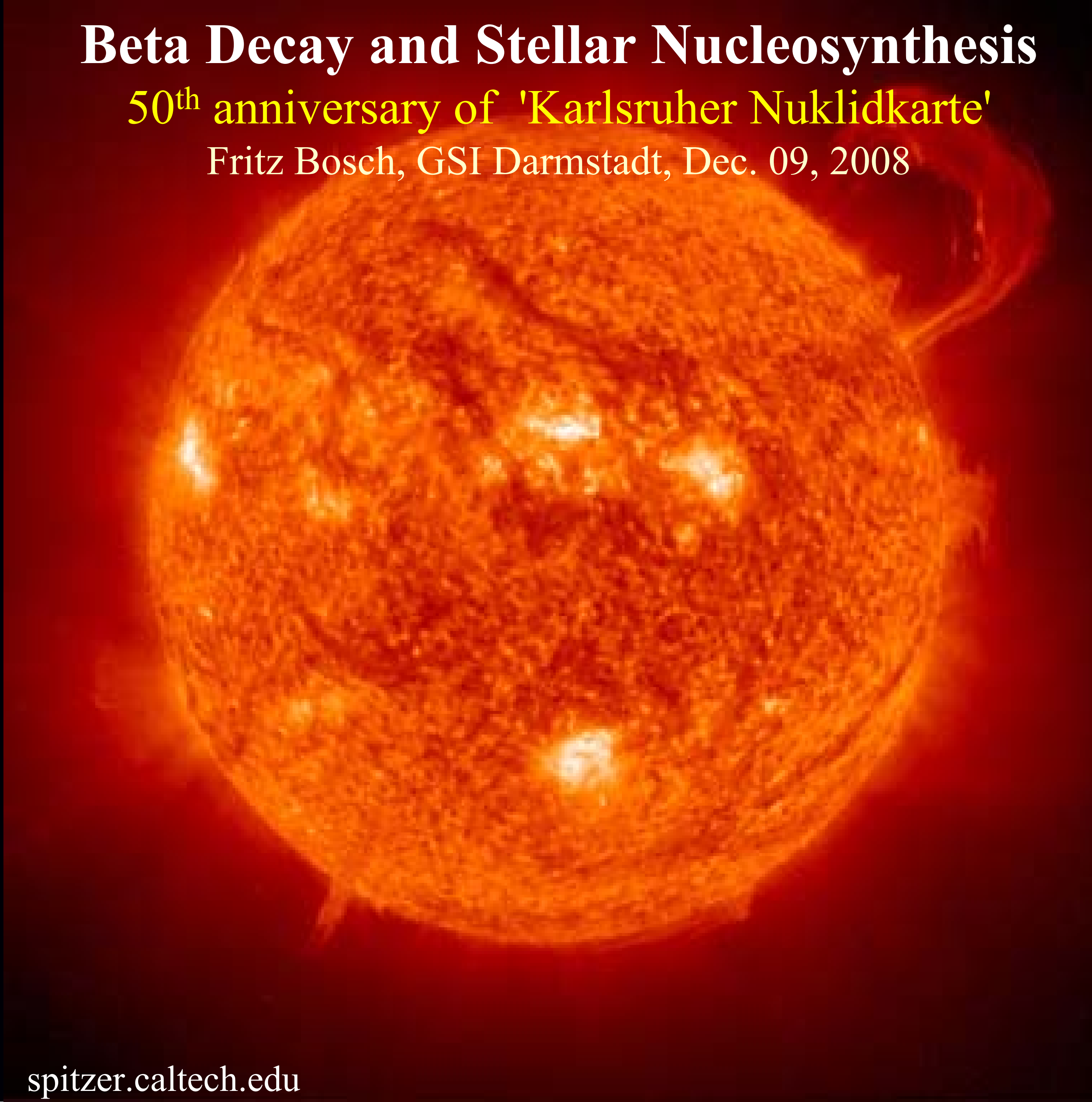
Beta Decay and Stellar Nucleosynthesis

50th anniversary of 'Karlsruher Nuklidkarte'

Fritz Bosch, GSI Darmstadt, Dec. 09, 2008



spitzer.caltech.edu

Outline

1. Impact of beta (β) decay on the stellar synthesis of the nuclides
   - the fundamental β decay in stars : $p + p \rightarrow {}^2H^+ + \beta^+ + \nu_e$
   - stellar nucleosynthesis via β decay in the s -, rp -, r- process

2. Beta decay of stored, cooled, highly-charged nuclides (GSI)
   - production, storage, cooling of unstable, highly-charged ions
   - electron-capture decay (EC) of single H-like and He-like ions

Honey..where are you coming from ?

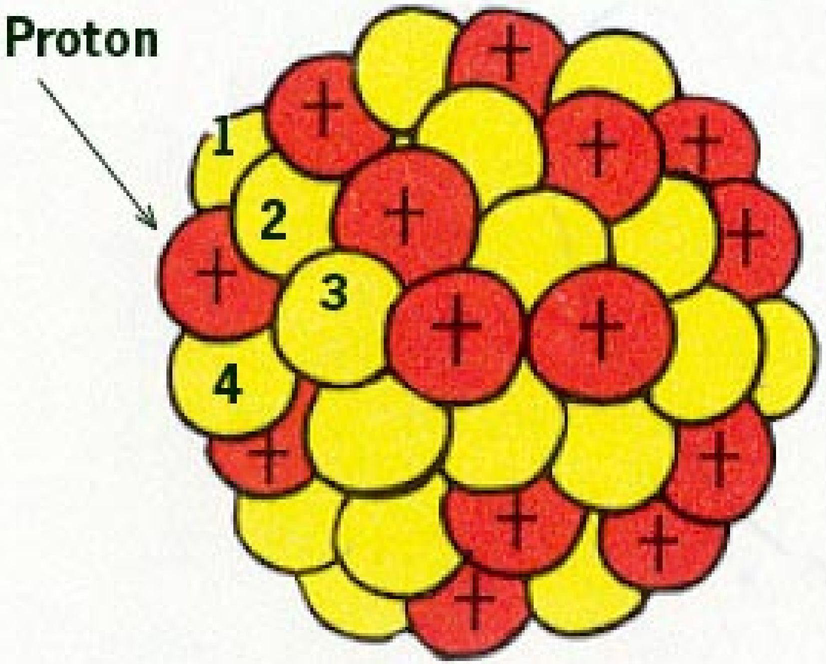
..I'm stardust

..Oh !! That sounds strange..

Be careful! You're not from a better-class family..

1. Beta decay: transmutation proton (p) ↔ neutron (n)

Mass (nucleus) < Z · mass (p) + N · mass (n)



Nature **minimizes** the Mass → **n ↔ p**

Z protons (p) = element number

N neutrons (n)

Z + N = **A** = mass number

$\mathbf{n} \rightarrow \mathbf{p} + \beta^- + \nu_e{}^*$ (β^- decay)

$\mathbf{p} \rightarrow n + \beta^+ + \nu_e$ (β^+ decay)

$\mathbf{n + \nu_e \leftrightarrow p + \beta^-}$

A free proton is **stable**

A free neutron is unstable

Wolfgang Pauli

Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

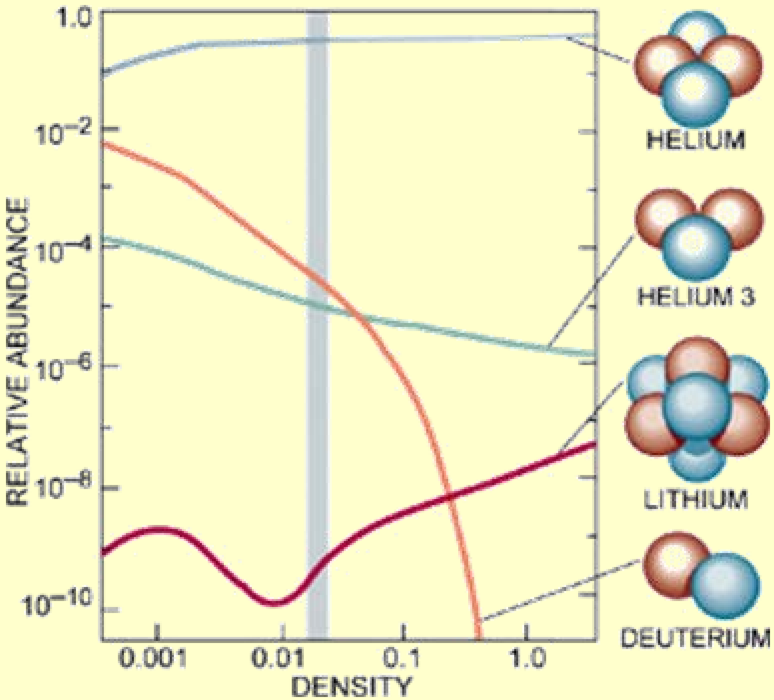
Zürich, 4. Dez. 1930
Gloriastrasse

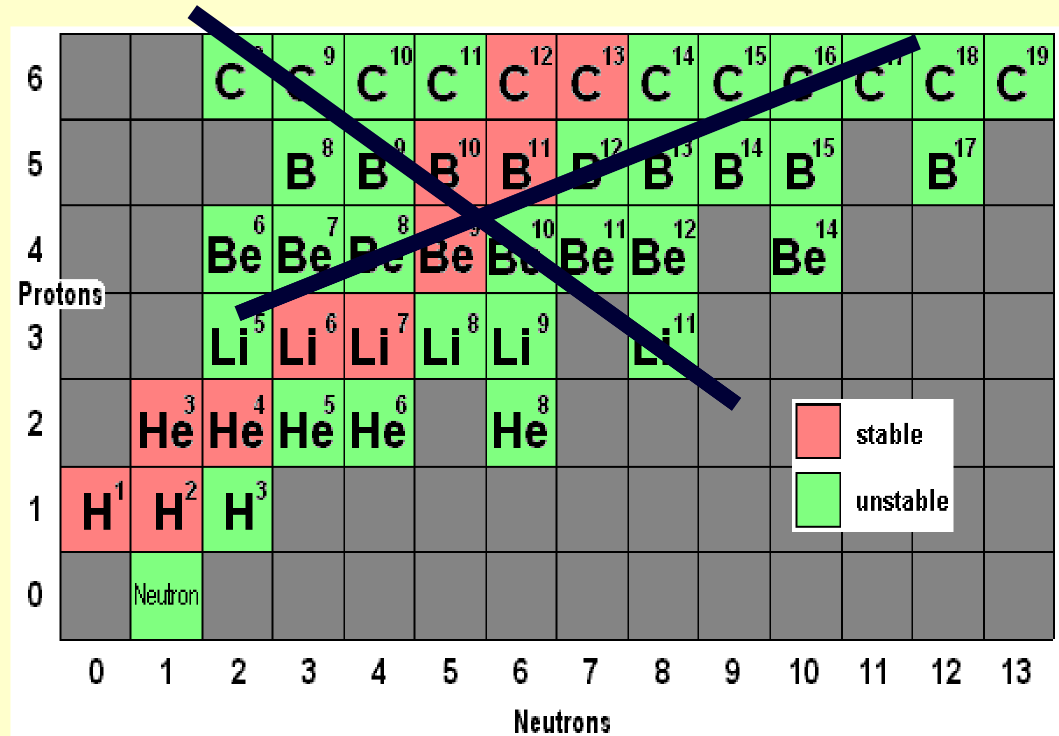
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

1. 'Primordial' formation of the elements hydrogen, helium, lithium within the first 200 s after the Big Bang at $T = 10^{11} \ldots 10^{9}$ K

$n \leftrightarrow p$ ('thermal equilibrium')





astro.berkeley.edu

Nucleosynthesis ceases for some 100 million years

Coulomb repulsion at decreasing T becomes too large

There are no stable nuclei at mass numbers A = 5 and A = 8

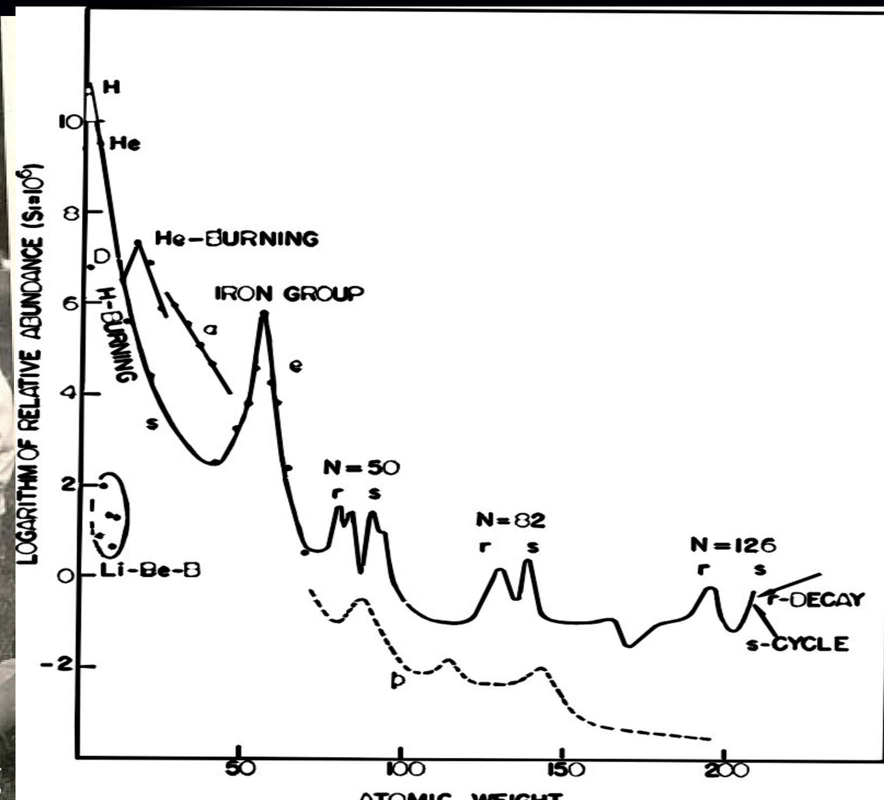
Free neutrons **disappear**: $n \rightarrow p + \beta^- + \nu_e^*$ (neutron half-life = 10 min.)

1. The 'second attempt' some 100 million years later

nasa.gov

1. We' re all made of stardust

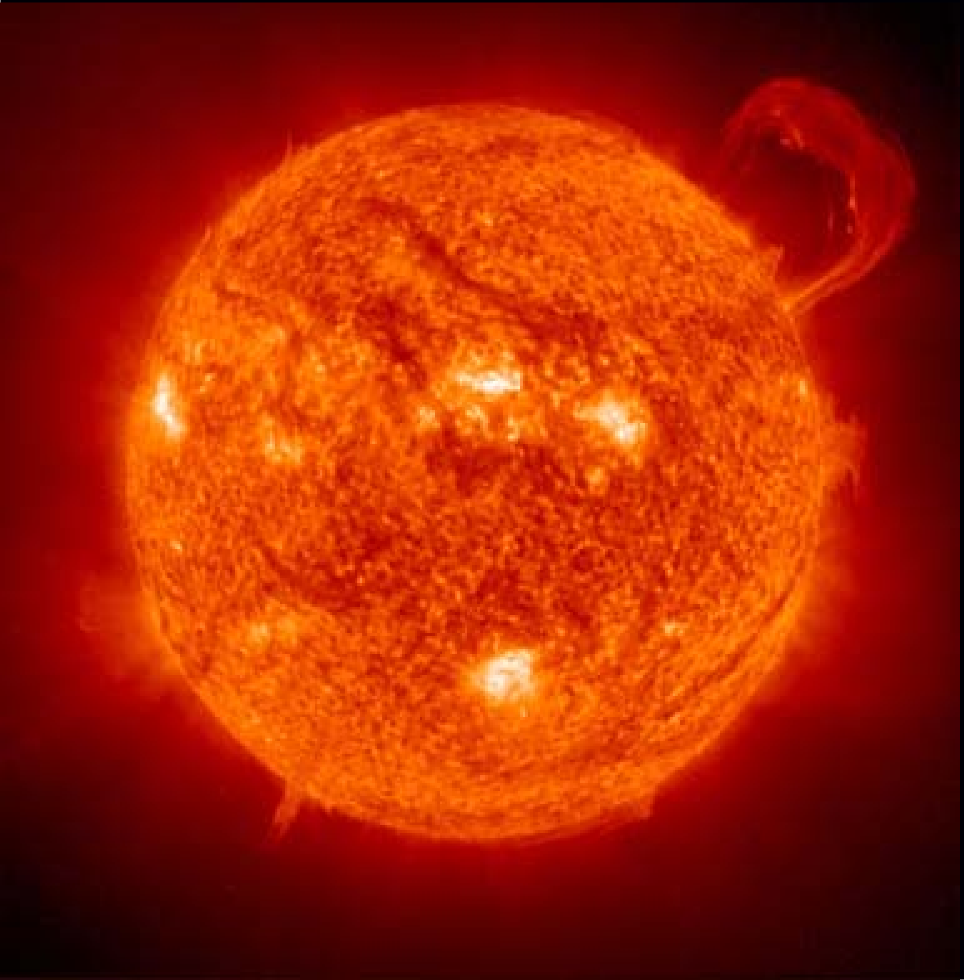
how this happened we know since exactly 50 +1 years*



* E. Margaret Burbidge, Geoffrey R. Burbidge, William A. Fowler, Fred Hoyle

Review of Modern Physics **29** (1957) 587 **B^{2}FH**

1.The fundamental β decay in stars or the great enigma



Centre of a sun-like star:

Temperature of about $15 \cdot 10^6$ K

Plasma of protons$^+$, electrons$^-$, He^{++}

Density: $150 g/cm^3 = 10^{26}$ p and e^- $/cm^3$
Mean distance : 2×10^{-9} cm

No free neutrons !!

$p \rightarrow n + \beta^+ + \nu_e$ not possible !

$p + p \rightarrow {}^2He^{++}$ unstable !

$p + {}^4He^{++} \rightarrow {}^5Li^{3+}$ unstable !

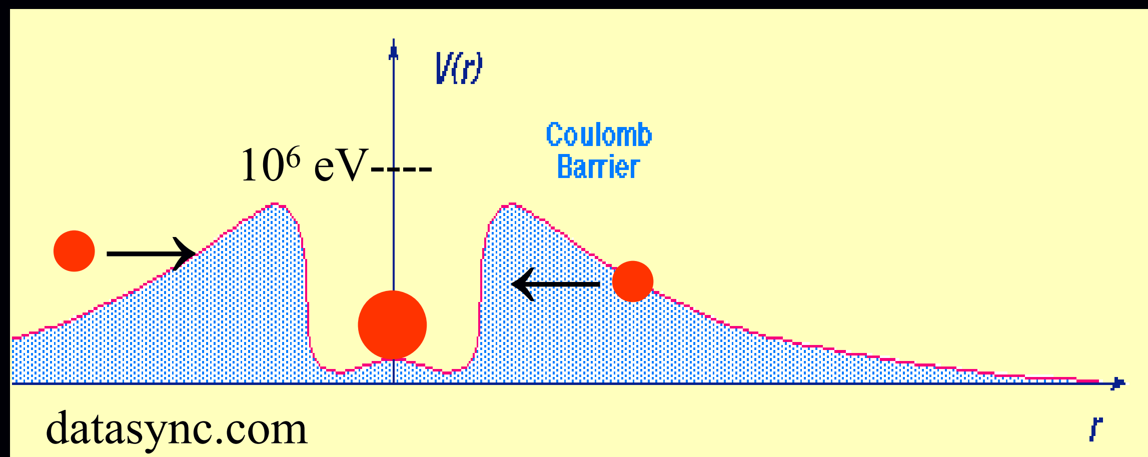
${}^4He^{++} + {}^4He^{++} \rightarrow {}^8Be^{4+}$ unstable !

How will this mystery be resolved ??

1. The fundamental β decay : $p + p \rightarrow {}^2H^+ + \beta^+ + \nu_e$

1. Two protons must come into contact

2. To overcome the Coulomb hill they need about **10^6 eV**



Their mean energy amounts to only $1.5 \cdot 10^3$ eV

→ there are a few protons with (much) **larger energy** (Maxwell distr.)

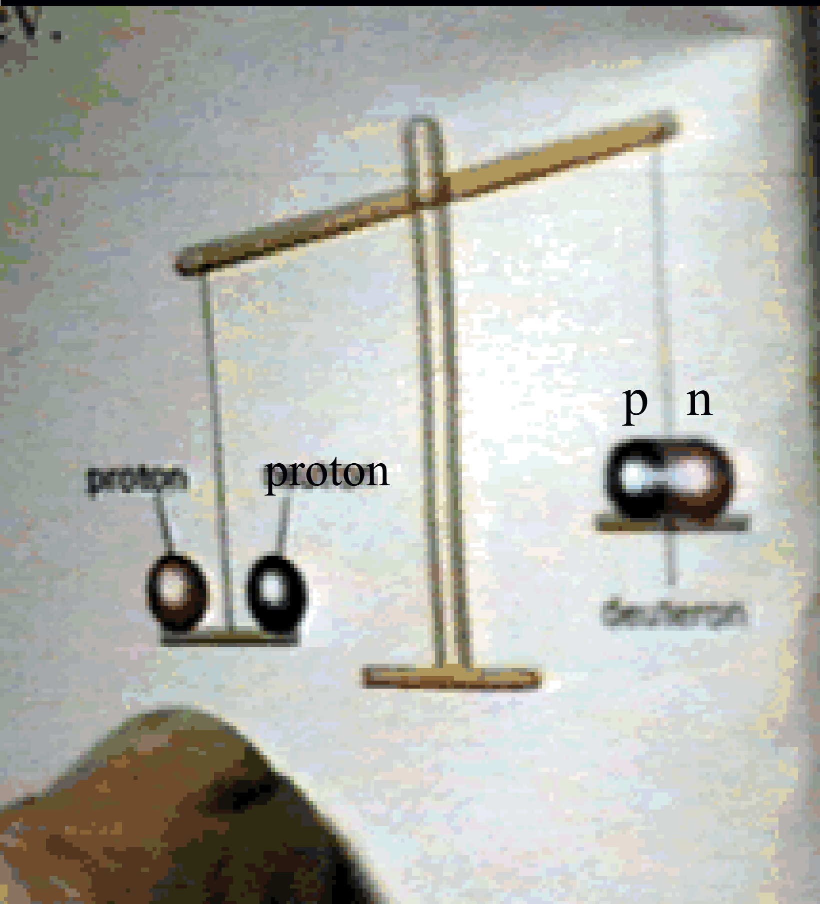
→ there is the 'tunneling effect' of quantum mechanics helping

But the protons have only a 'time' of **10^{-16} s** to meet – then they will be pushed away

Within this eye-glance one of the protons gets a neutron according to:

$$p + (p \rightarrow \mathbf{n} + \beta^+ + \nu_e) \rightarrow (\mathbf{p} + \mathbf{n})^+ + \beta^+ + \nu_e \rightarrow {}^2\mathbf{H}^+ + \beta^+ + \nu_e + 0.42\ \text{MeV}$$

though a **free** neutron has a **larger rest mass** than a free proton !



because proton and (transmuted) neutron form a **'deuteron$^+$' = ^{2}H$^+$**

whose rest mass is smaller than the rest mass of two free protons

For a proton the probability to become a deuteron is **extremely small**:

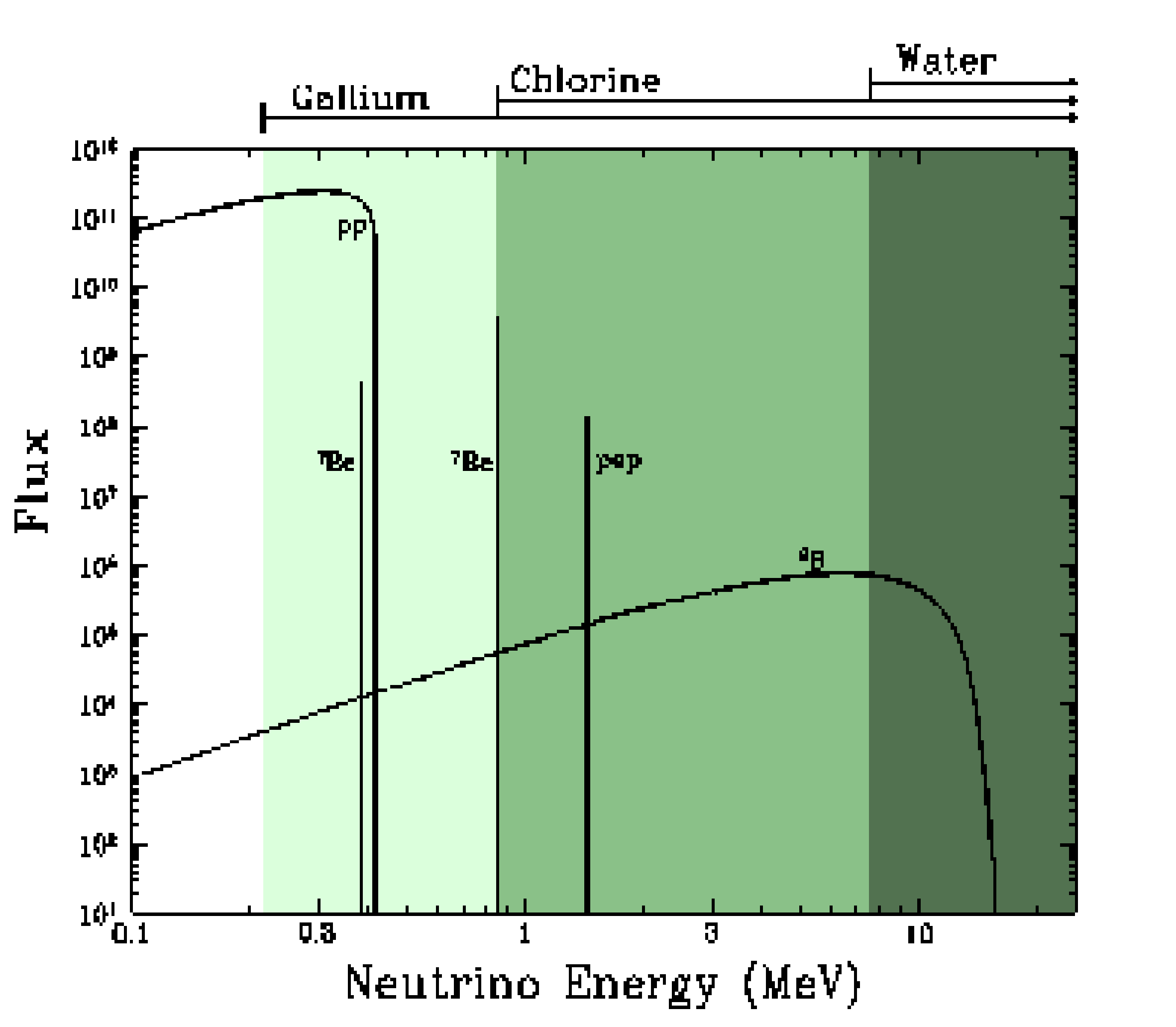
it tries it about **10^{34} times** for nothing

it has to 'wait' about 10 billion years !

$$^2H^+ + p \rightarrow {}^3He^{++} + 5.5\ \text{MeV}$$

$$^3He^{++} + {}^3He^{++} \rightarrow {}^4\mathbf{He}^{++} + 2p + 13\ \text{MeV}$$

1. β decay is also decisive for the next steps of nucleosynthesis



$^{3}He + {}^{4}He \longrightarrow {}^{7}Be$

$^{7}Be + e^{-} \longrightarrow {}^{7}Li + \nu_e$ 'EC'

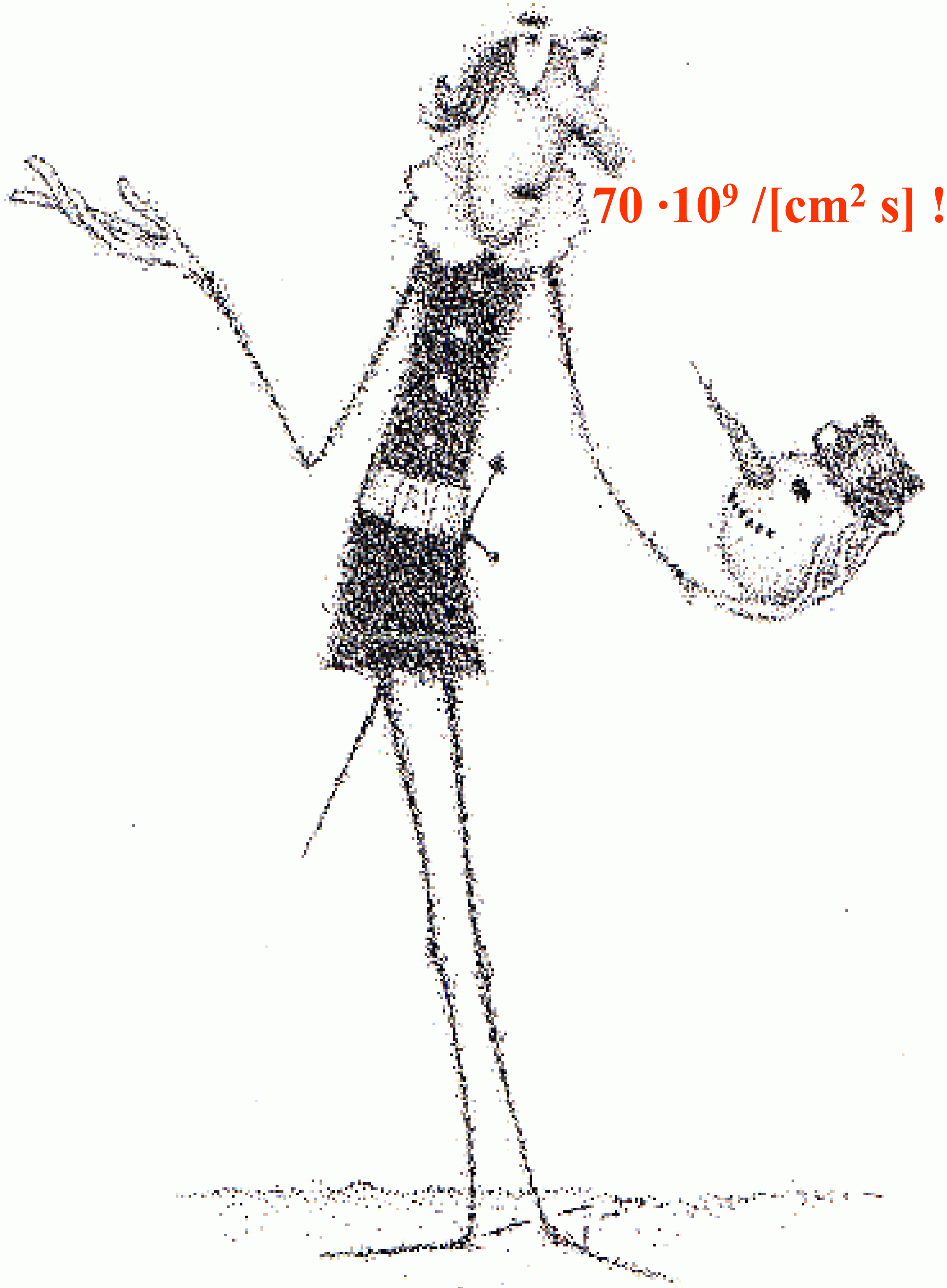
$^{7}Be + p \longrightarrow {}^{8}B$

$^{8}B \longrightarrow {}^{8}Be + \beta^{+} + \nu_e$ 'β^{+}'

Neutrinos from the sun by

$p + p \longrightarrow {}^{2}H = 2 \cdot 10^{38}/s$

On the earth = $70 \cdot 10^{9}$ /[$cm^2 s$]

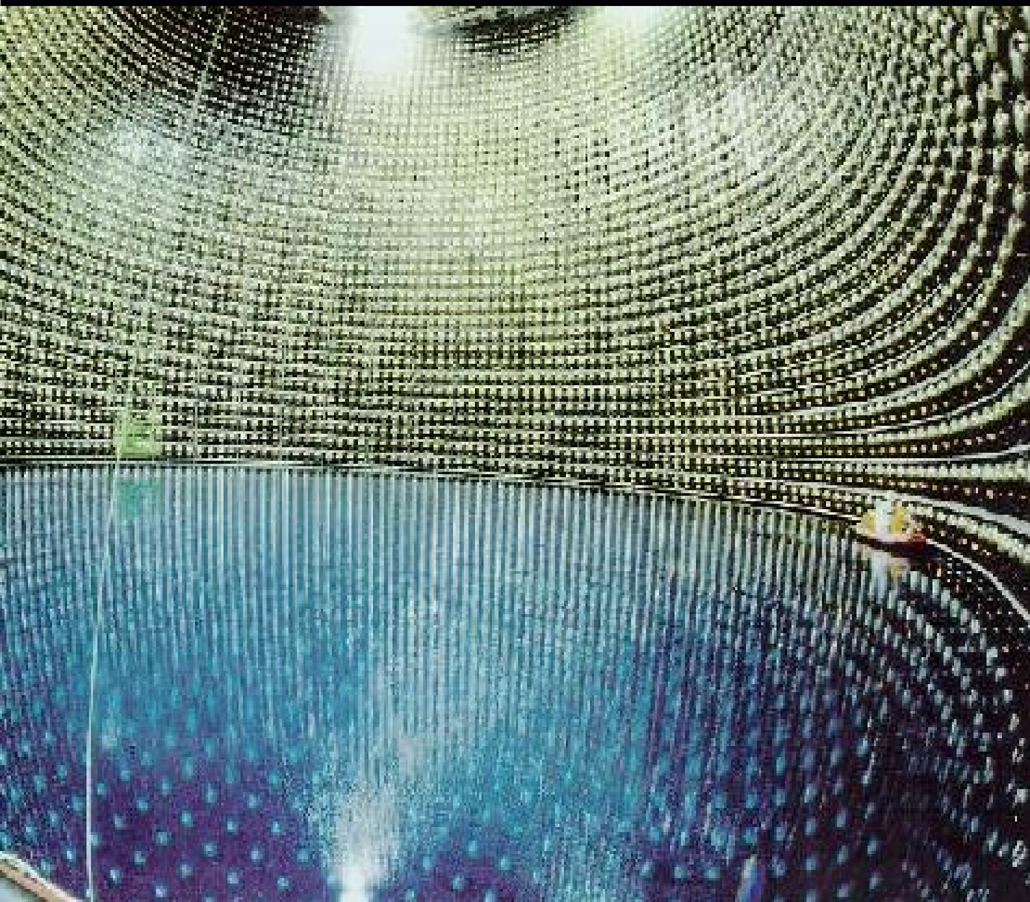


karl-koppe.de

"There are more things
in heaven and earth,
Horatio,
than are dreamt of
in your phantasy"

W. Shakespeare, Hamlet

The most important but never communicated news:



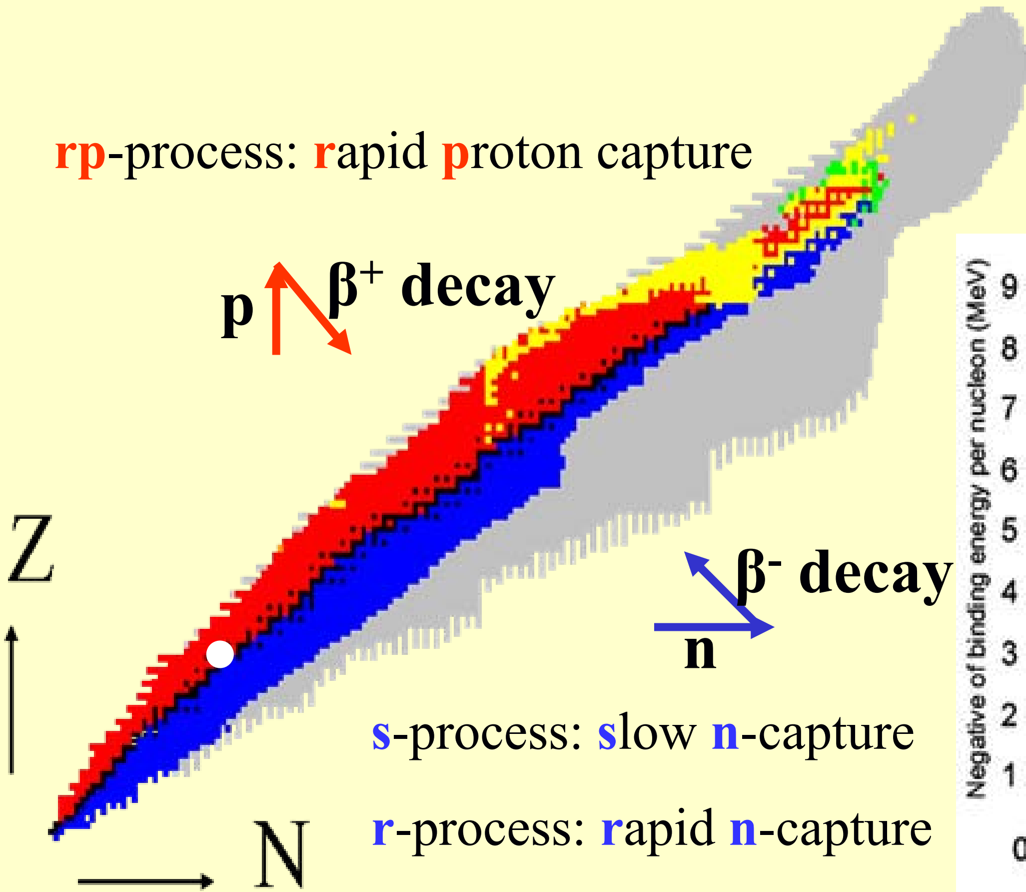
Neutrino detector at Kamioka, Japan

Only the **neutrino flux** measured by many thousands of detectors in underground laboratories, monitors the **actual** energy production of the sun !

1. **Deuteron ^{2}H** → fusion to ^{4}He, ^{12}C...^{56}Fe (massive stars)

What happens beyond iron ?

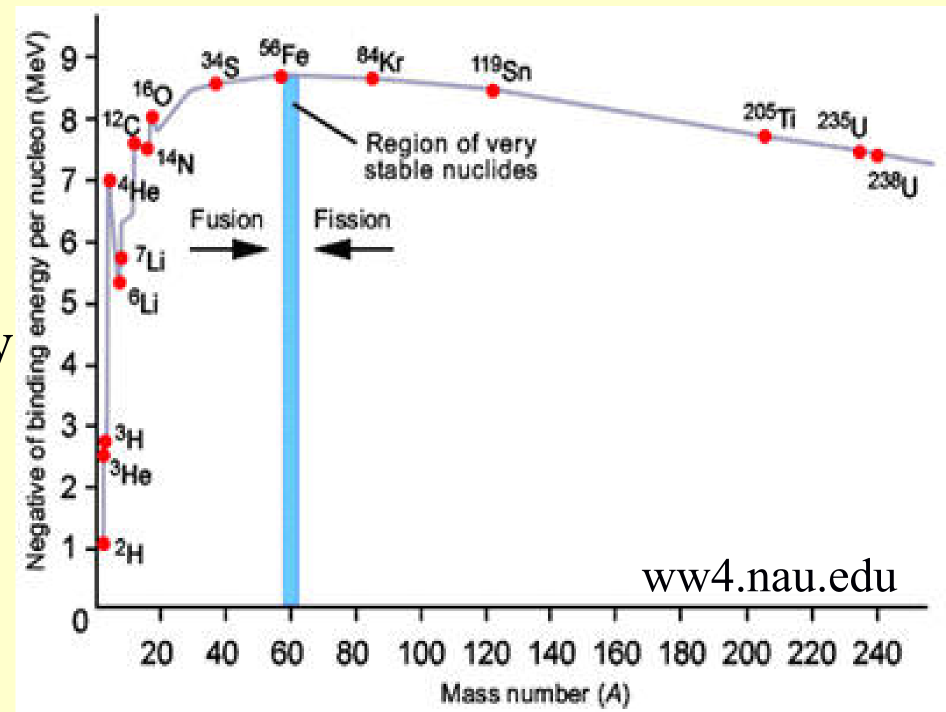
rp-process: **r**apid **p**roton capture



s-process: **s**low **n**-capture

r-process: **r**apid **n**-capture

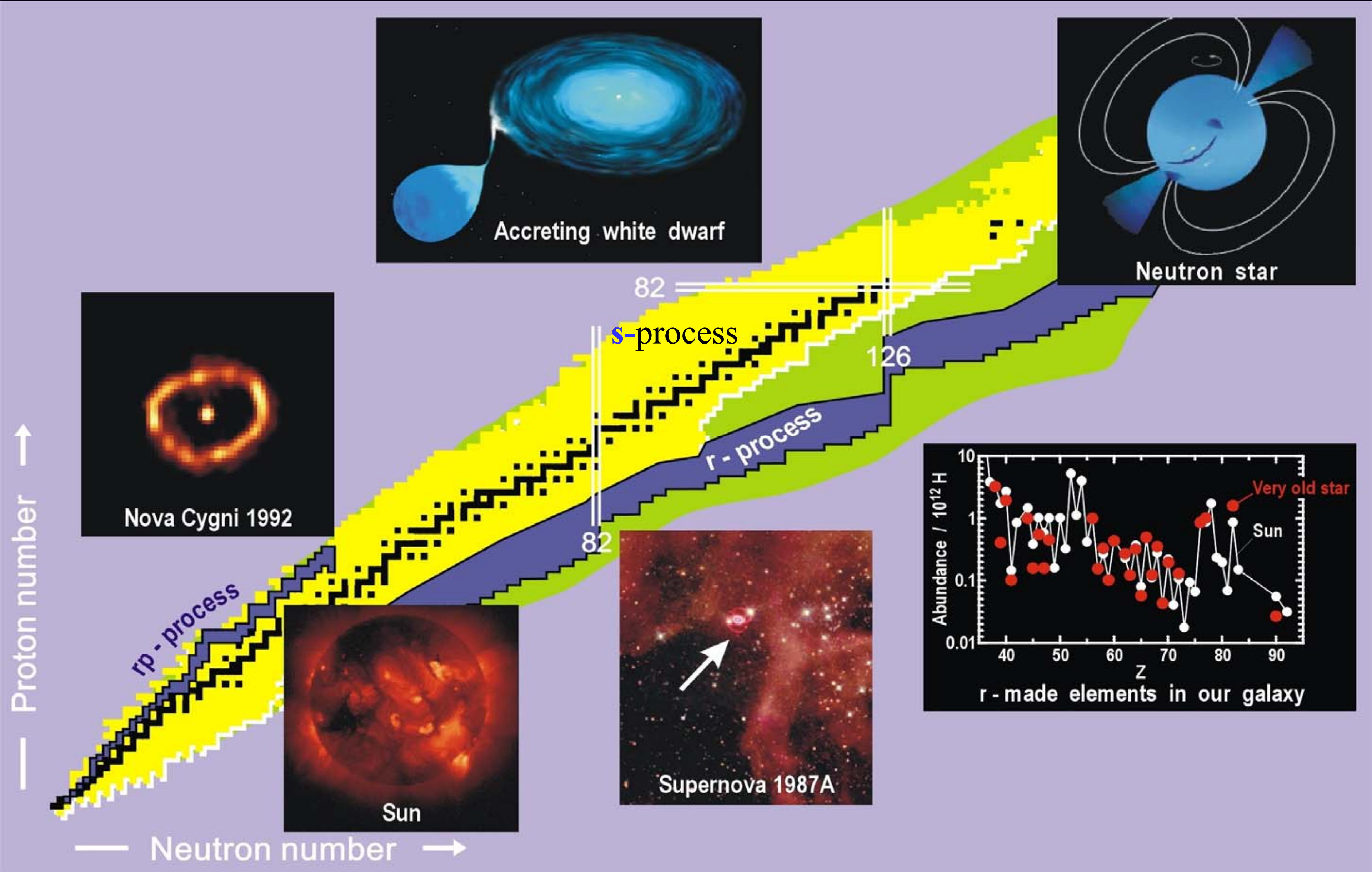
wwwnsg.nuclear.lu.se



All nuclides **beyond iron** are created in the stars, **in particular by β decay,** capture of free protons and neutrons, and by α-decay (yellow) and fission (green)

$n \rightarrow p + \beta^{-} + \nu_e^{*}$ (β^{-} decay, blue); $p \rightarrow n + \beta^{+} + \nu_e$ (β^{+} decay, red)

1. Sites of stellar nucleosynthesis



Outbreak of a Supernova in the Large Magellan Cloud, February 1987

1. Addressing the pathways of stellar nucleosynthesis

Key parameters:

Masses, β - lifetimes, n- capture-, n-γ cross-sections

Masses determine the **pathways**
of s -, rp - and r - processes

β- lifetimes the accumulated **abundances**

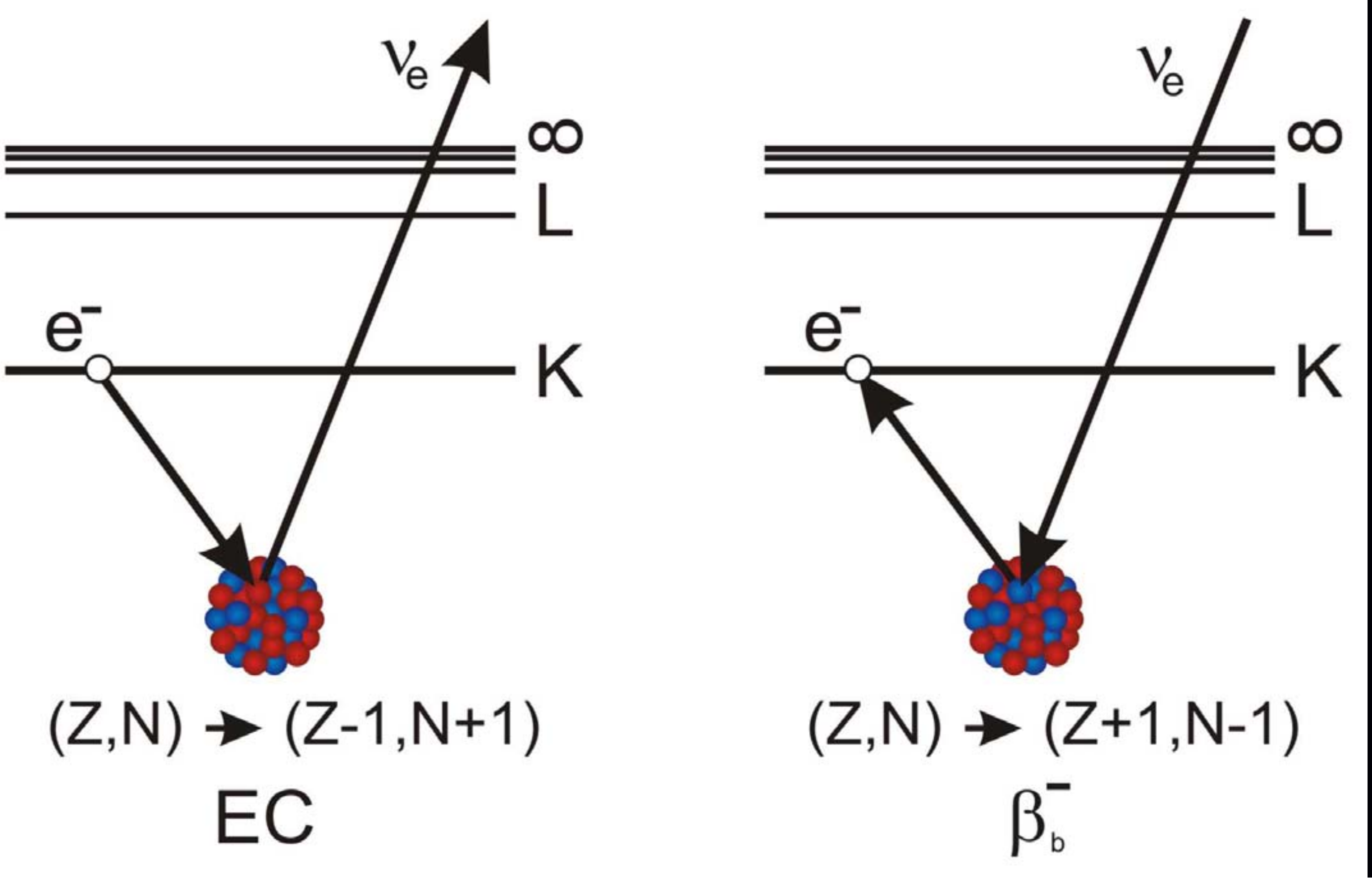
Hot stellar environment : **atoms are highly-ionized**

→ providing **highly-charged** unstable nuclides
storing them by **preserving** the charge state → getting the **β - lifetime**

2. β decay of **highly-charged** nuclides : **bound** β decay (β_b)

$p + e^-_b \rightarrow n + \nu_e$ (EC); time-mirrored EC: $n + \nu_e \rightarrow p + e^-_b$ (β_b)

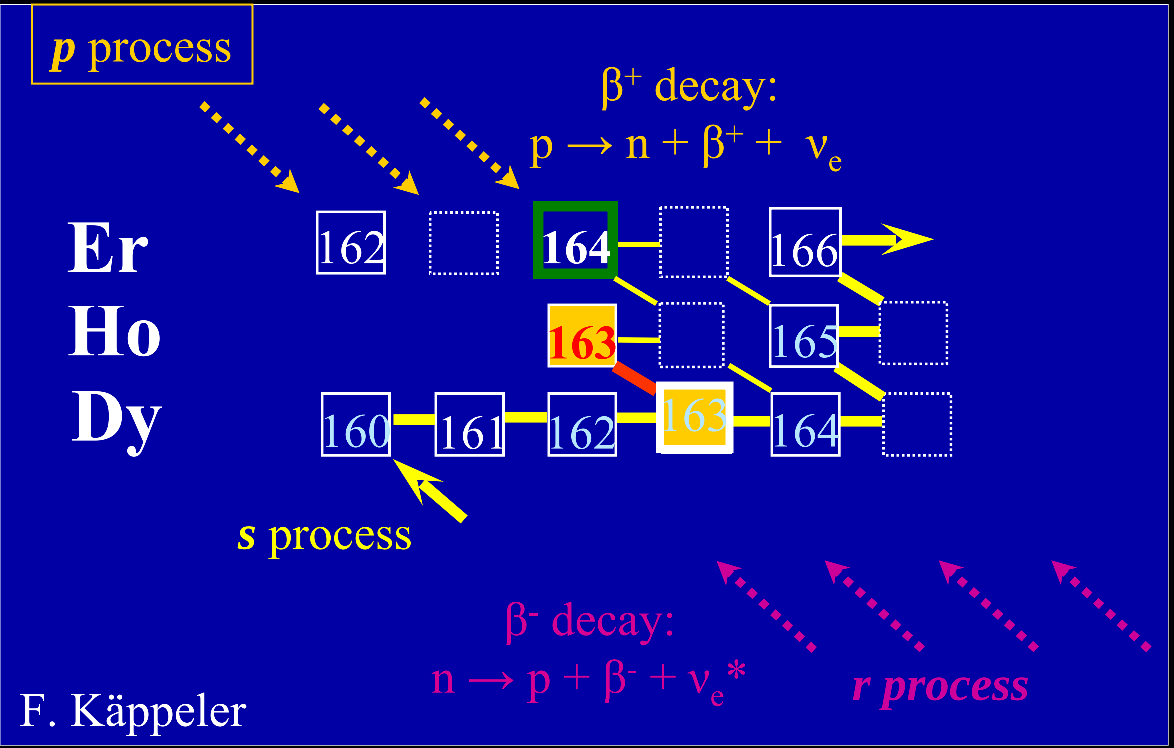
β_b is a **two-body** β decay-mode, significant for highly-charged atoms
→ decay energy, decay probability different from neutral atoms
→ stable neutral atoms can get unstable, if bound electrons are removed



Neutral ^{163}Dy :
stable

Bare $^{163}Dy^{66+}$:
$T_{1/2}$ = 48 d

2. Half-life of β_b decay provides s-process temperature T



From the half-life of bare $^{163}Dy^{66+}$

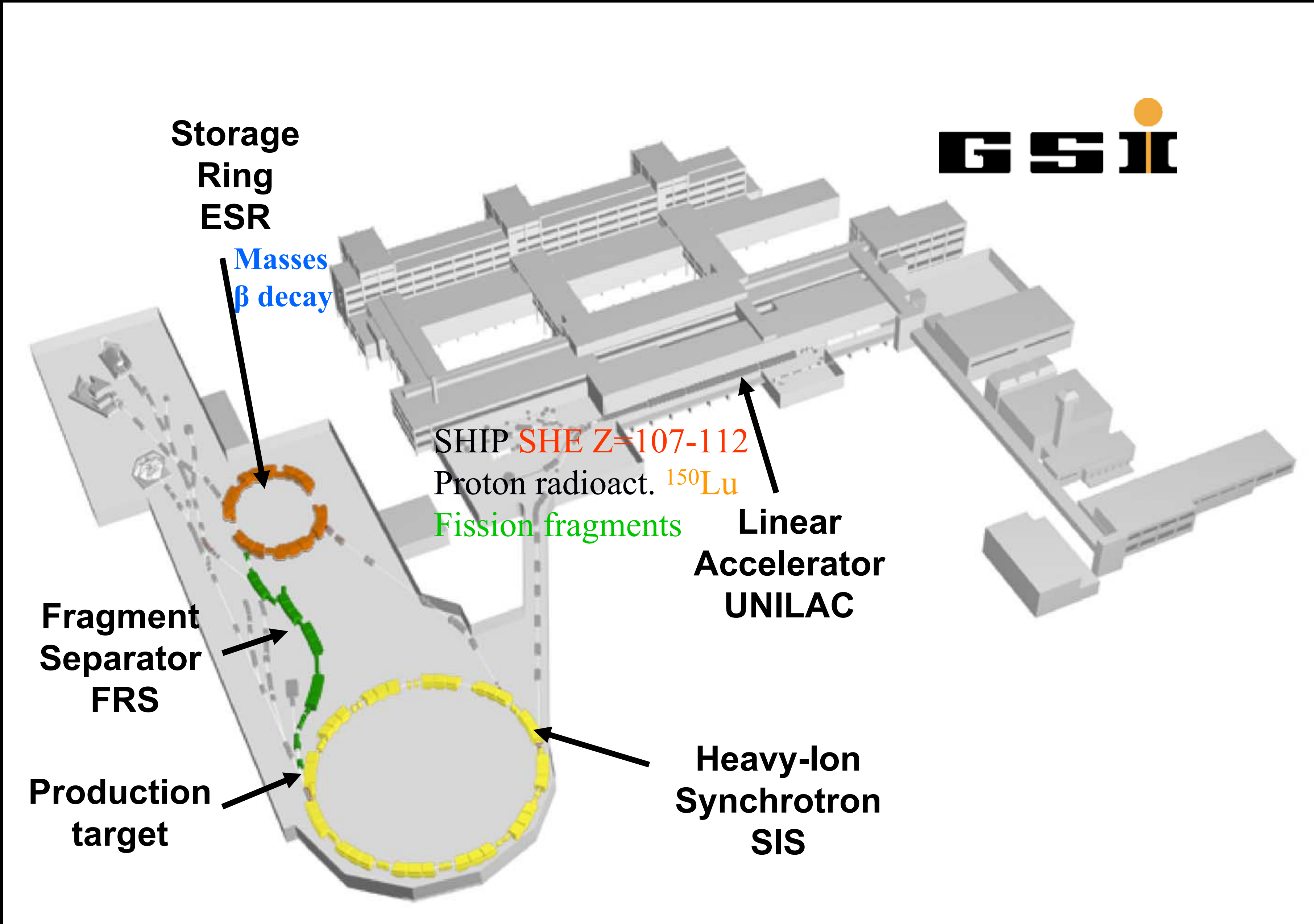
and abundances of ^{163}Dy, ^{163}Ho and ^{164}Er

$\rightarrow T_{163} = (35 +- 5)\ 10^7$ K

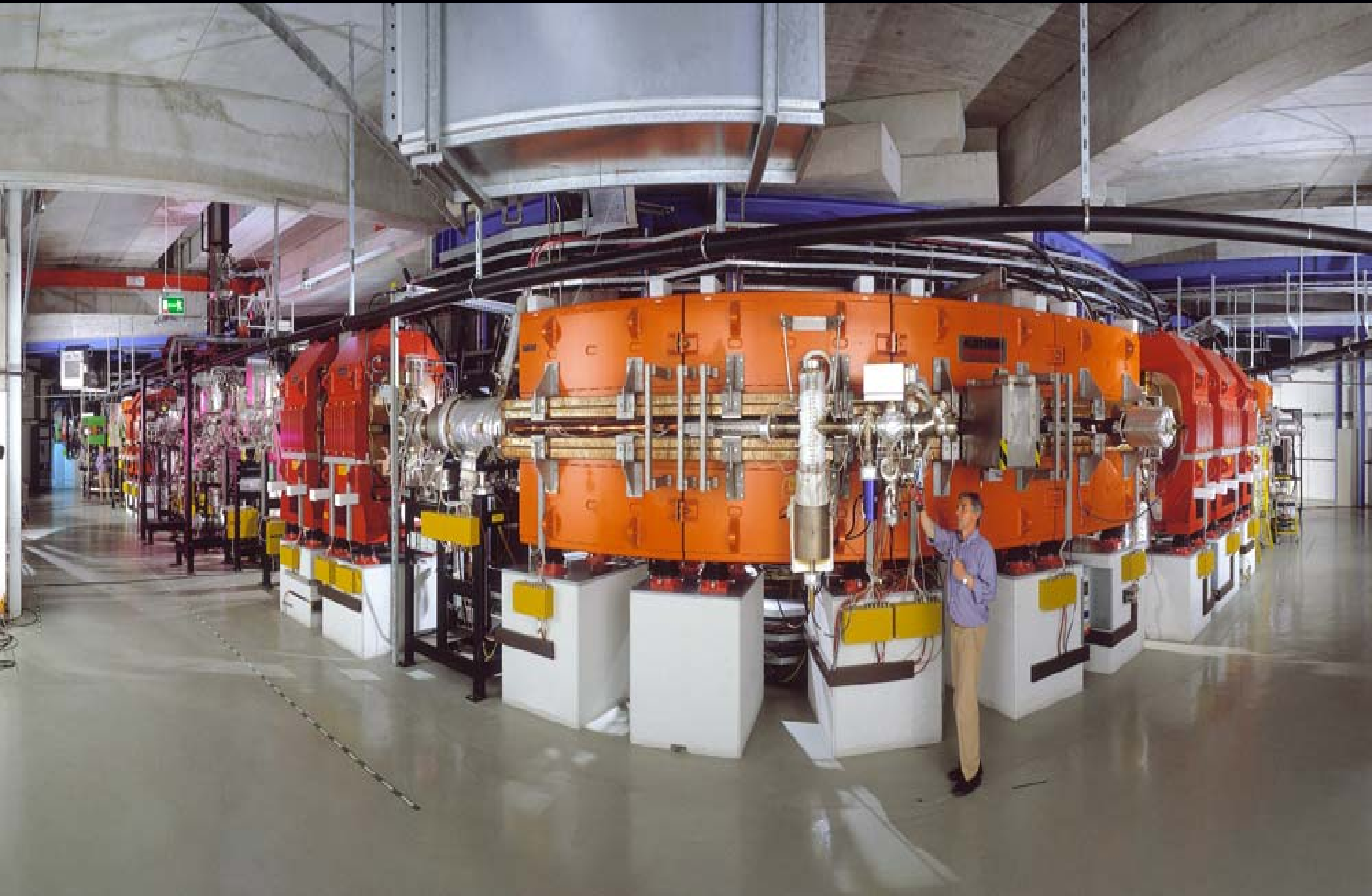
s- process branching at A = 163
caused by β_b decay of highly-charged ^{163}Dy

M. Jung et al., Phys. Rev. Lett. **69**, 2164 (1992)

2. Production, storage, cooling of unstable, highly-charged ions

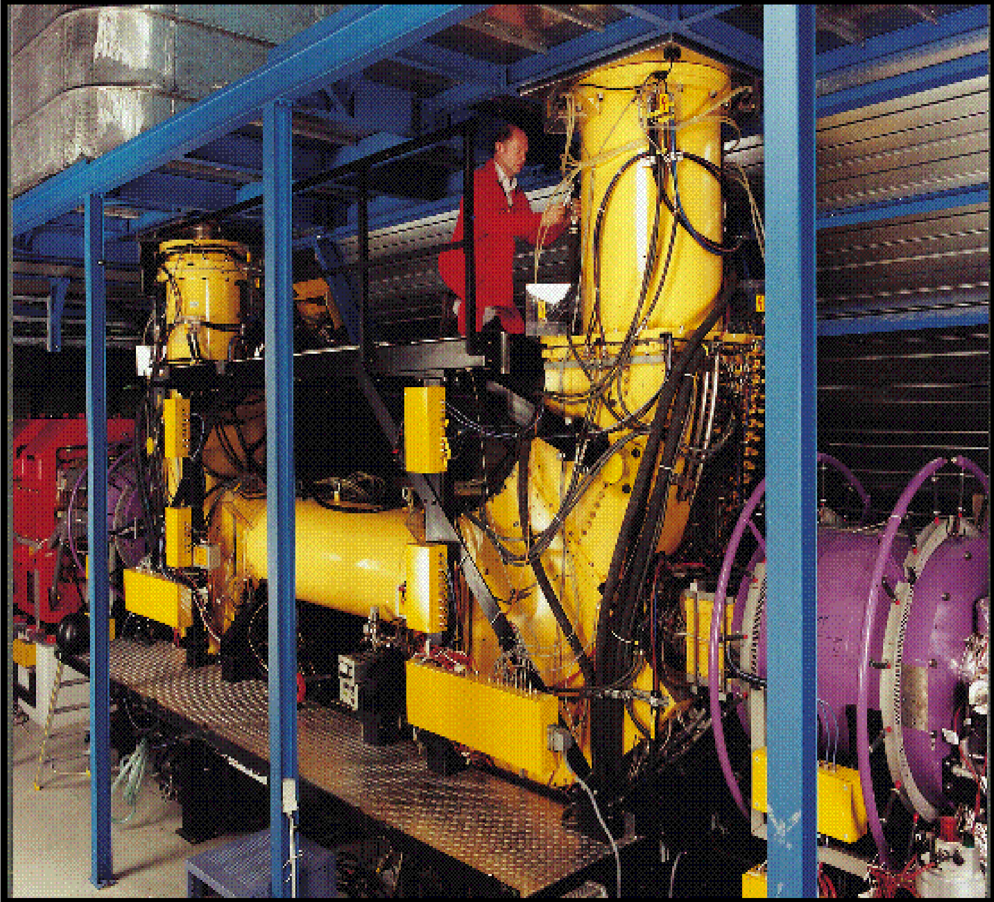


2. The ESR : E_{max} = 420 MeV/u, 10 Tm, e^- -, stochastic 'cooling'



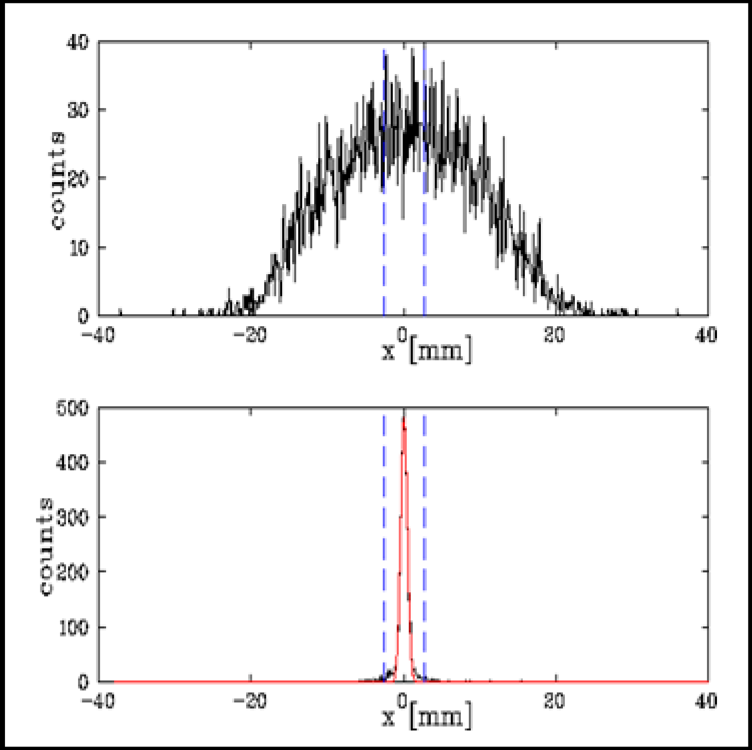
2. Cooling': enhancing the phase space density

Electron cooling: G. Budker, 1967 Novosibirsk

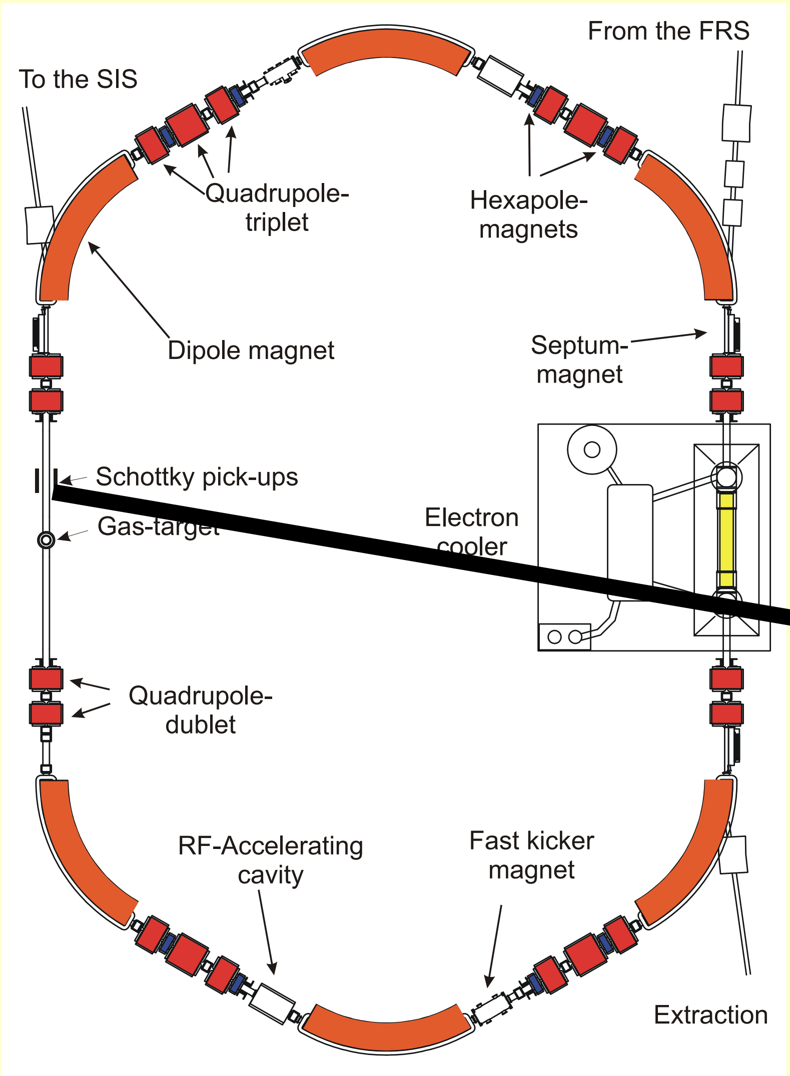


Momentum exchange

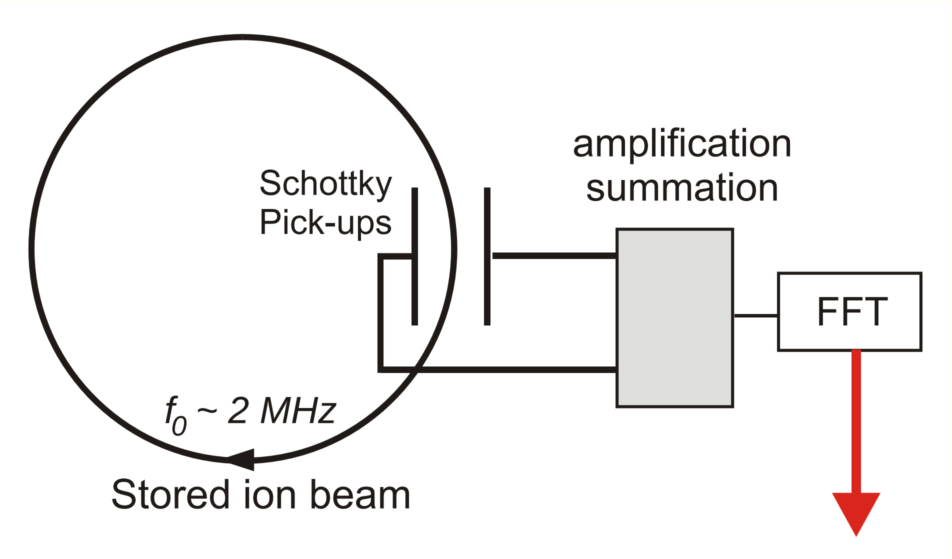
with a cold, collinear e^- beam. The ions get the **sharp velocity** of the electrons, small size and small angular divergence



2. Schottky Mass-and Lifetime Spectrometry SMS



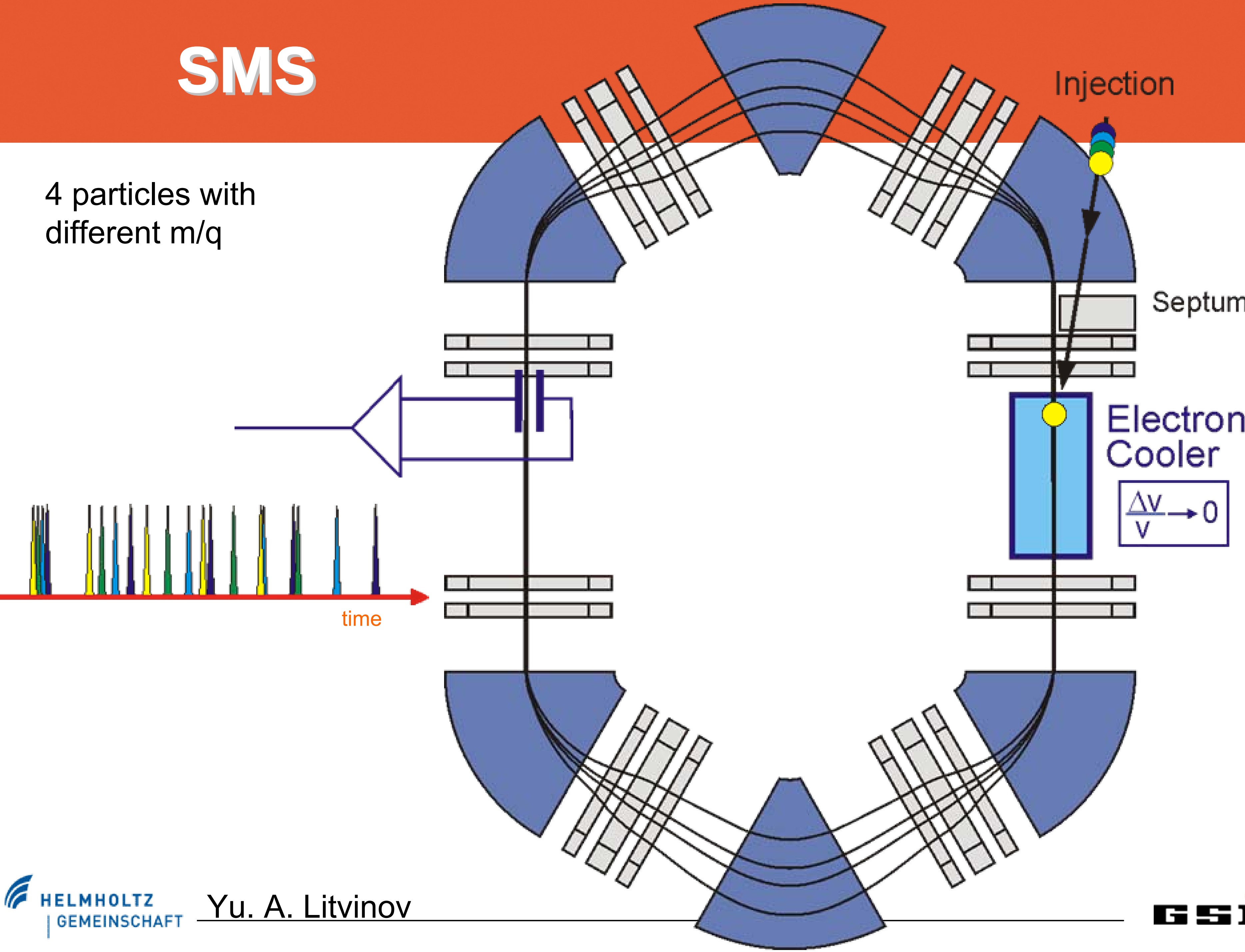
$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$



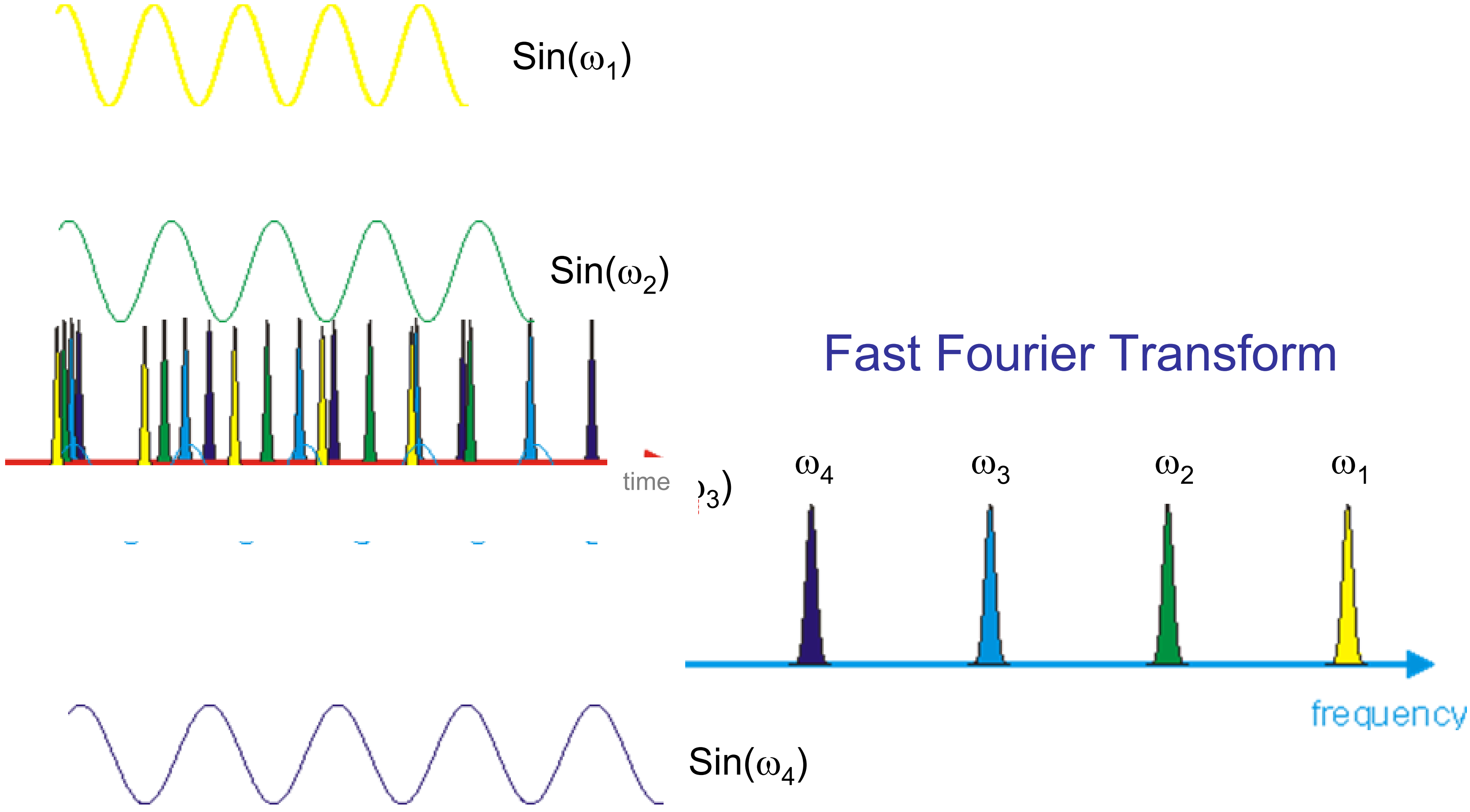
Continuous digitizing and storage of raw data

SMS

4 particles with
different m/q

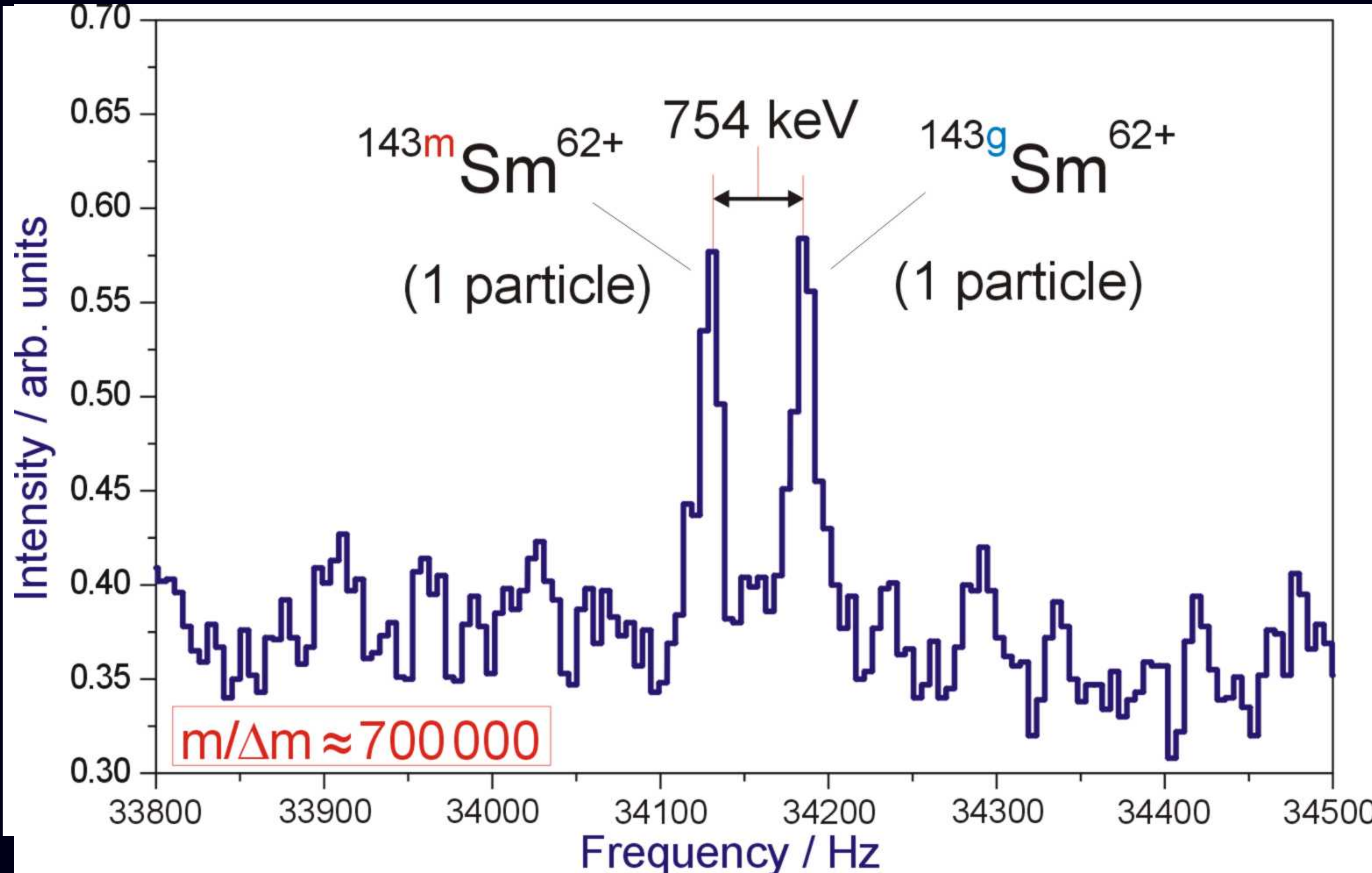


SMS



Sin(ω1)
Sin(ω2)
time
Fast Fourier Transform
ω4
ω3
ω2
ω1
frequency
Sin(ω4)

Schottky frequency spectra



2. Measured Mass Surface

Masses of more than 1100 Nuclides were measured

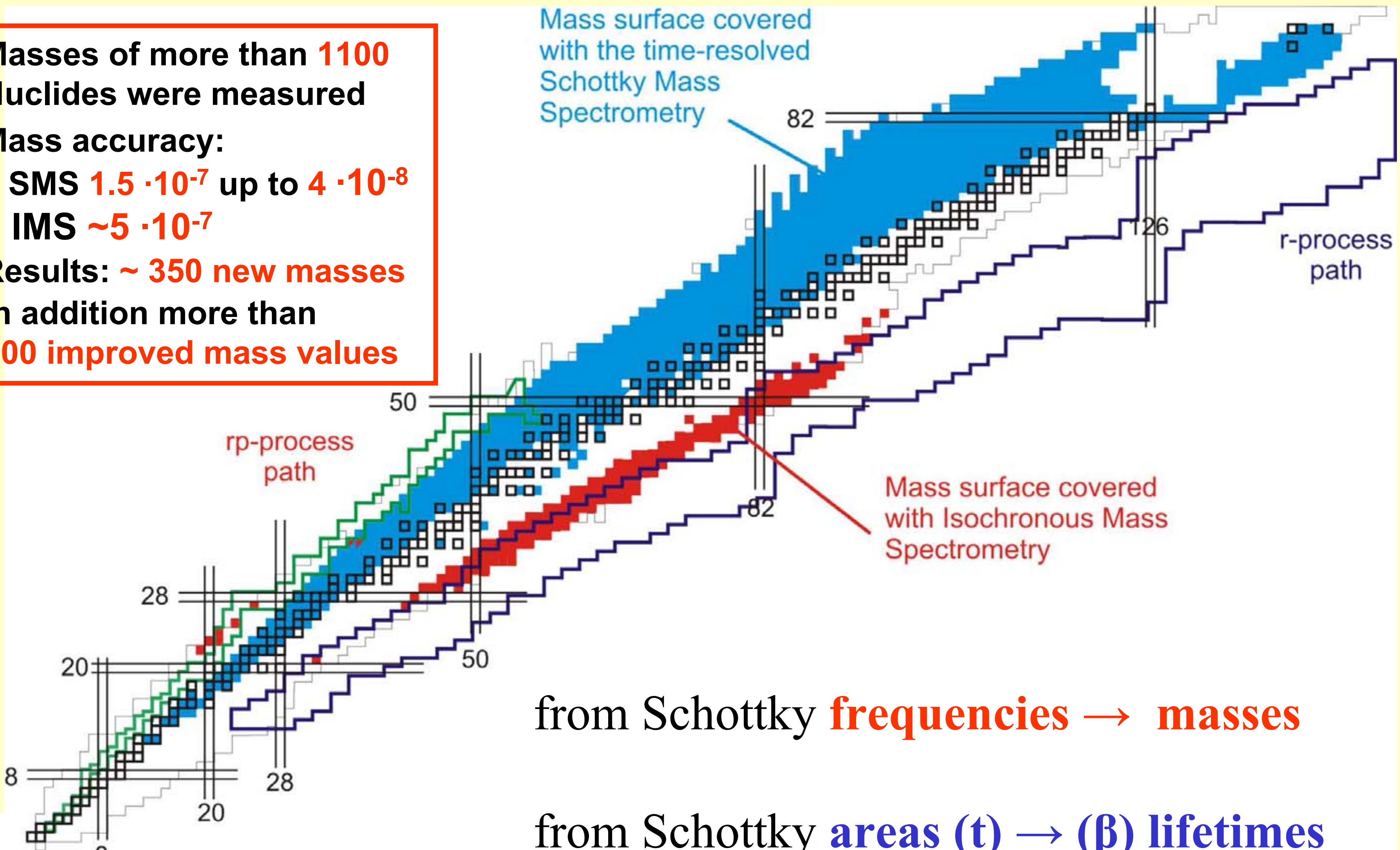
Mass accuracy:

SMS 1.5 $\cdot 10^{-7}$ up to 4 $\cdot 10^{-8}$

IMS ~5 $\cdot 10^{-7}$

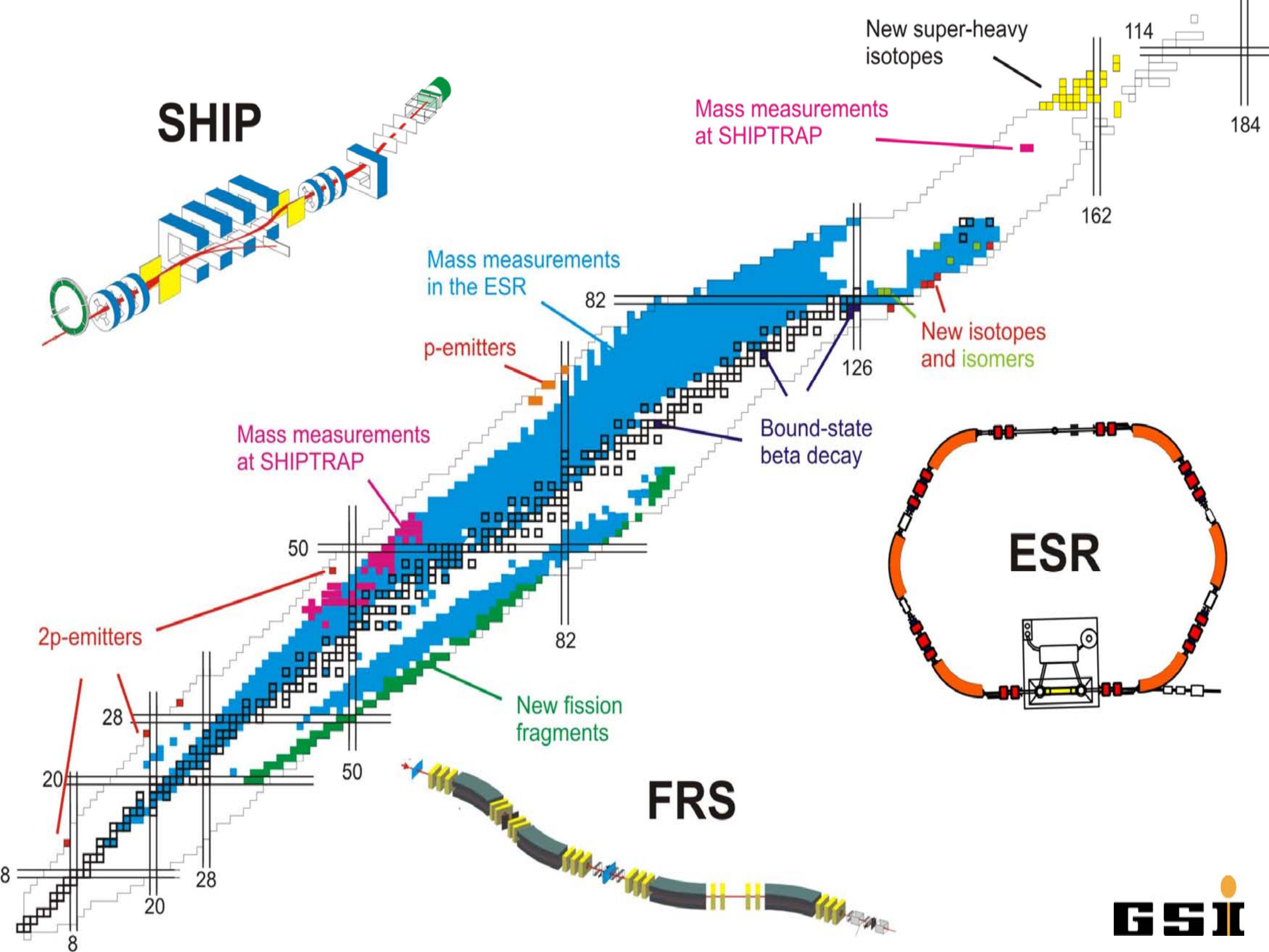
Results: ~ 350 new masses

In addition more than 300 improved mass values



from Schottky **frequencies → masses**

from Schottky **areas (t) → (β) lifetimes**



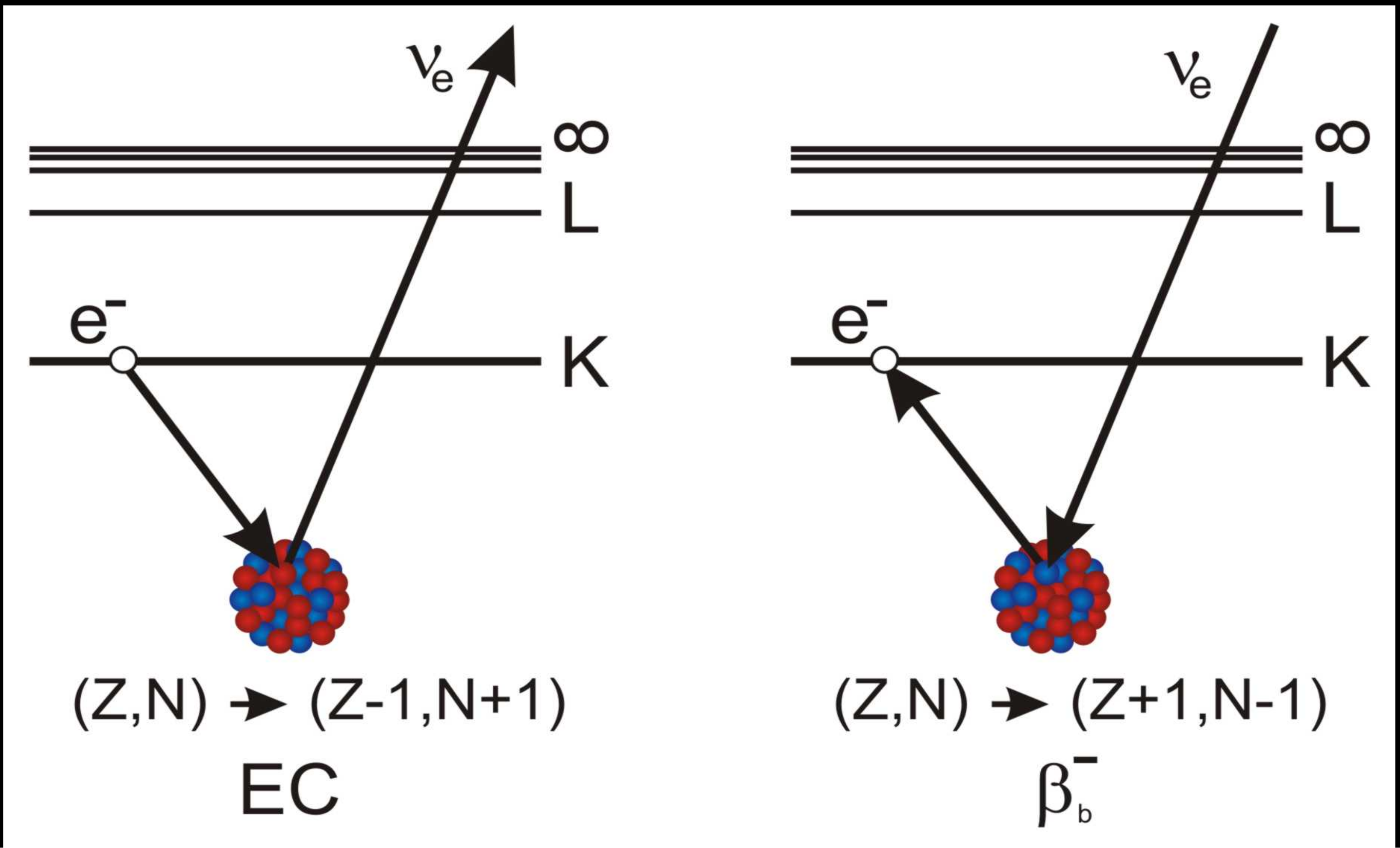
SHIP
New super-heavy isotopes
114
184
162
Mass measurements at SHIPTRAP
Mass measurements in the ESR
82
126
New isotopes and isomers
p-emitters
Bound-state beta decay
Mass measurements at SHIPTRAP
50
82
ESR
2p-emitters
28
20
50
New fission fragments
FRS
8
28
20
8
GSI

2. **Two-body** β decay: Electron Capture (EC), bound β decay (β_b)

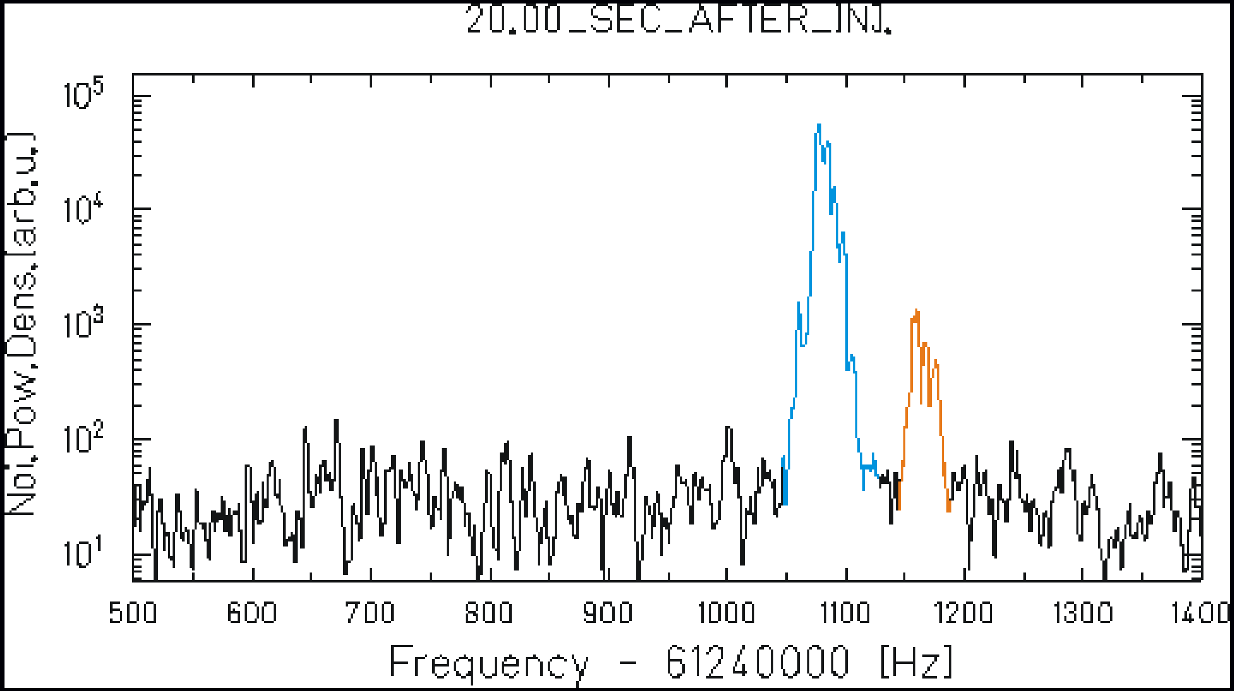
$$p + \beta^-_b \leftrightarrow n + \nu_e$$

ionic **charge state *q* preserved** in the decay

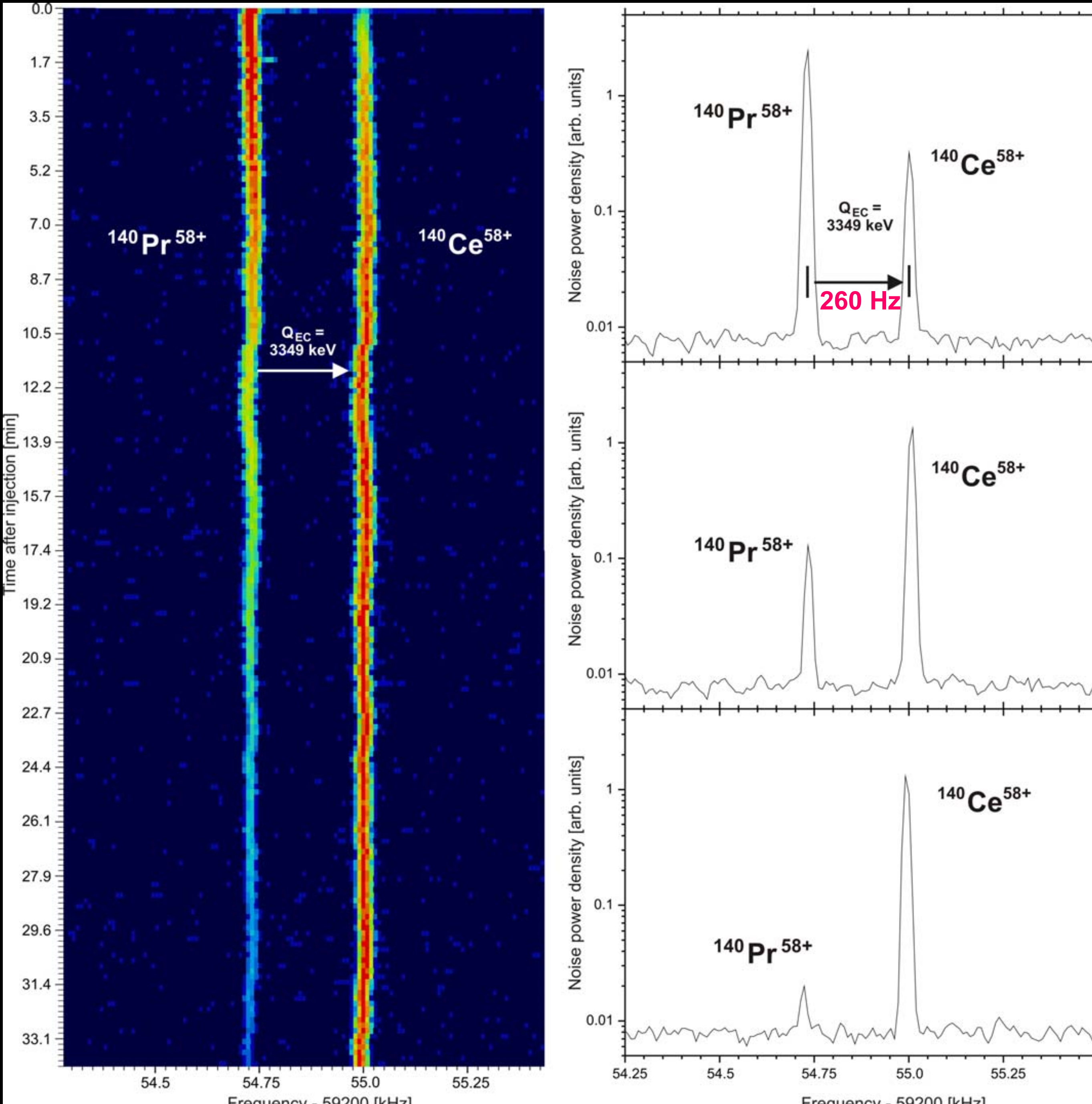
change of revolution frequency ***f*** only due to **change of the mass**



2. Cooling: β_b decay of bare $^{207}Tl^{81+} \rightarrow$ H-like $^{207}Pb^{81+}$



D. Boutin



revolution frequency *f*
→ **m/q**

charge ***q*** not changed

Change of ***f*** only due to **change of mass**

2. Ratio of EC -probabilty for H- and He-like ions

$\lambda_{\beta+}/\lambda_{EC}$ **(neutral atom) ≈ 1**

Expectations:

λ_{EC}**(H-like)/**λ_{EC}**(He-like) ≈ 0.5**

FRS-ESR Experiment

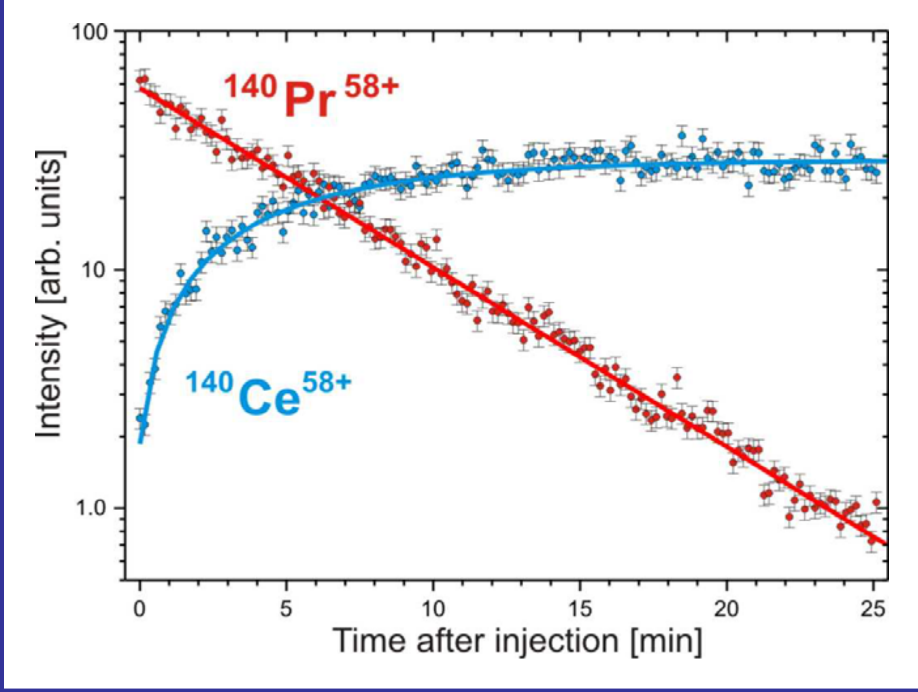
λ**(neutral) = 0.00341(1) s**$^{-1}$
G.Audi et al., NPA729 (2003) 3

$\lambda_{\beta+}$**(bare) = 0.00158(8) s**$^{-1}$ ***(decay of*** $^{140}Pr^{59+}$***)***

λ_{EC}**(H-like) = 0.00219(6) s**$^{-1}$ ***(decay of*** $^{140}Pr^{58+}$***)***

λ_{EC}**(He-like) = 0.00147(7) s**$^{-1}$ **(decay of** $^{140}Pr^{57+}$**)**

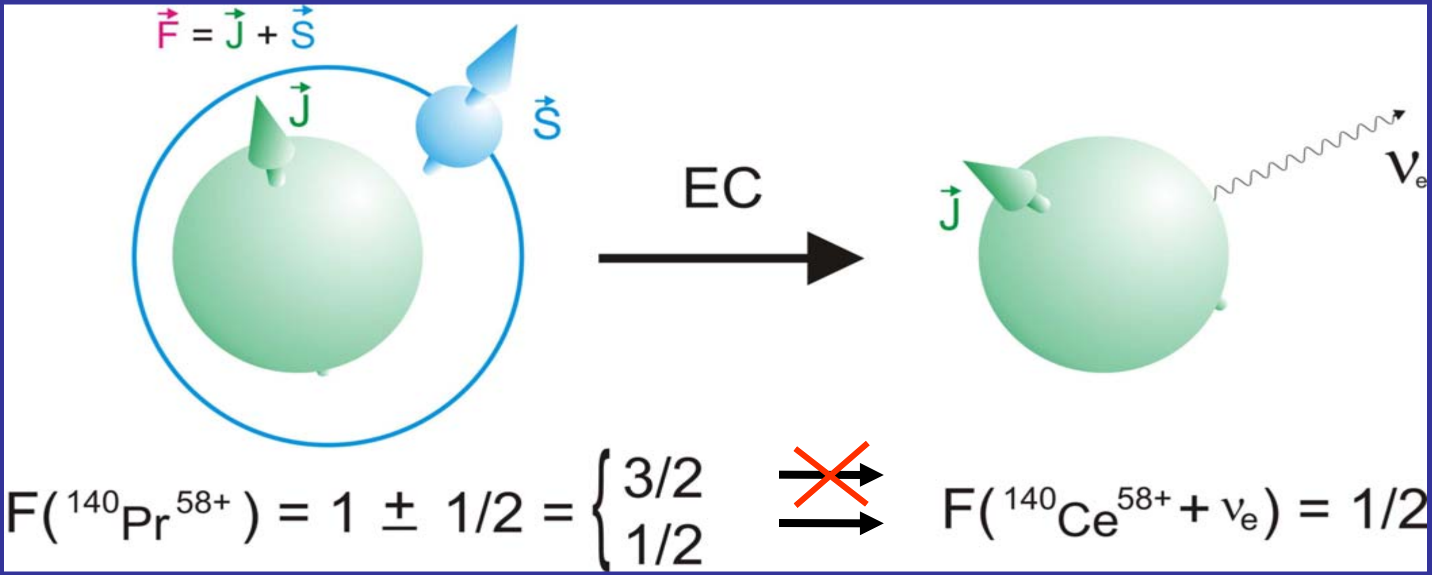
λ_{EC}**(H-like)/**λ_{EC}**(He-like) = 1.49(8)**



Yu. A. Litvinov et al.,
PRL **99,** 262501 (2007)

The H-like $^{140}Pr^{58+}$ ion decays faster than the neutral ^{140}Pr atom !

Gamow-Teller transition $1^+ \rightarrow 0^+$



S. Typel and L. Grigorenko

$\mu = +2.7812\ \mu_N$ (calc.)

Probability of EC Decay

Neutral ^{140}Pr: **P = 2.381**

He-like ^{140}Pr: **P = 2**

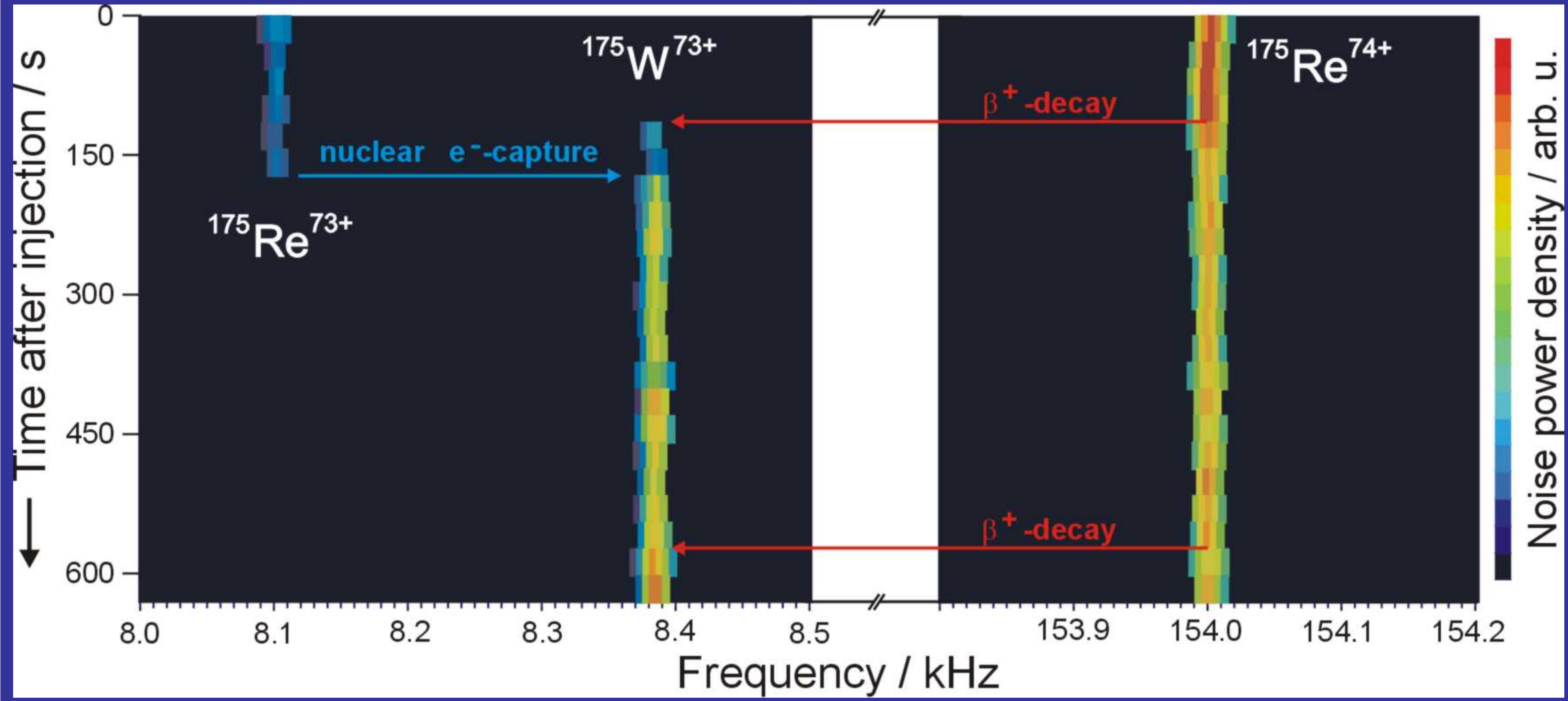
H-like ^{140}Pr: **P = 3**

Theory: Z. Patyk et al., PR **C77**, 014306 (2008)

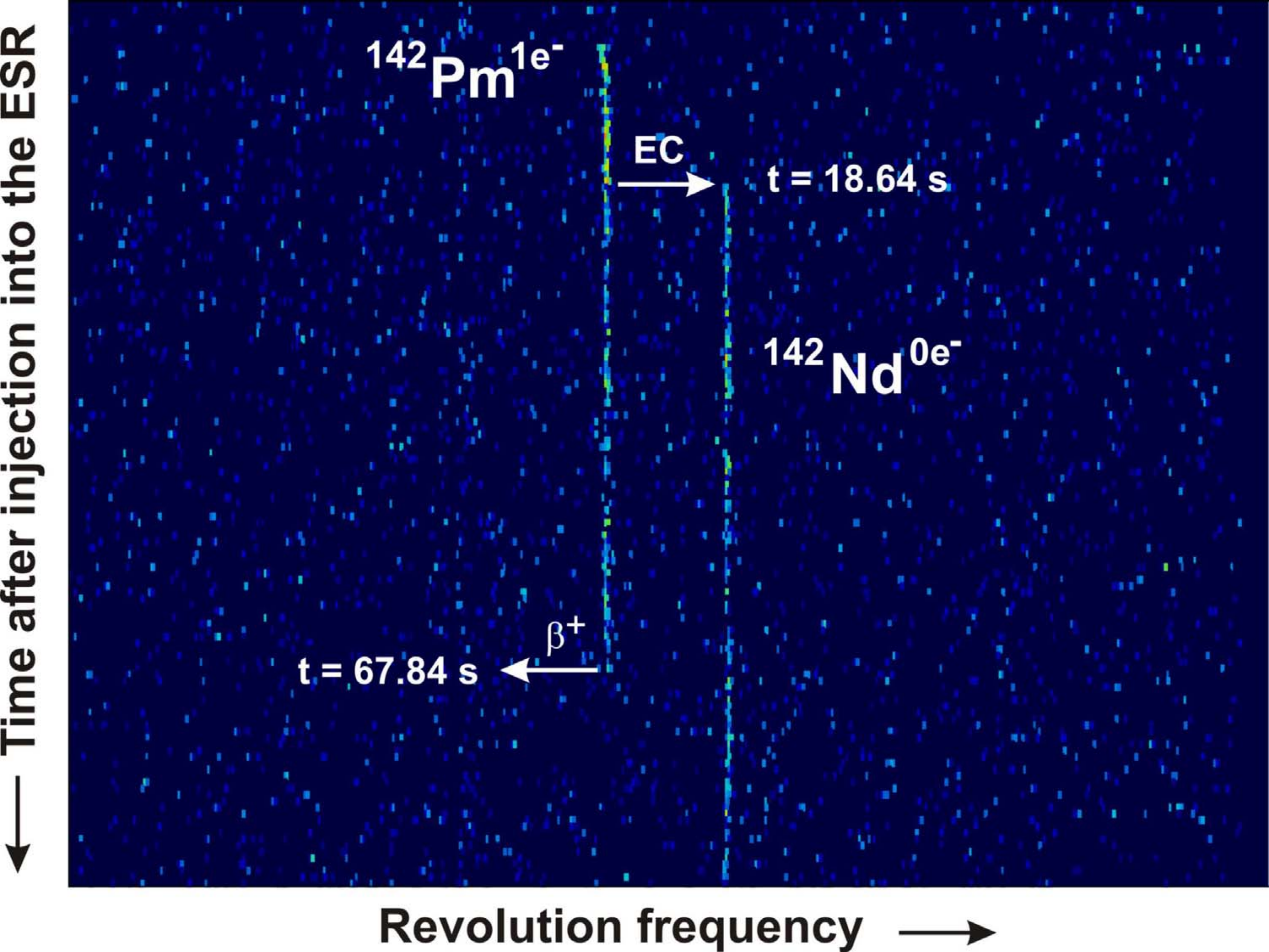
The H-like ion really decays by 20% faster than the neutral atom!

$\lambda(H)/\lambda(He) = (2I+1)/(2F+1)$

2. β decay of single stored and cooled ions

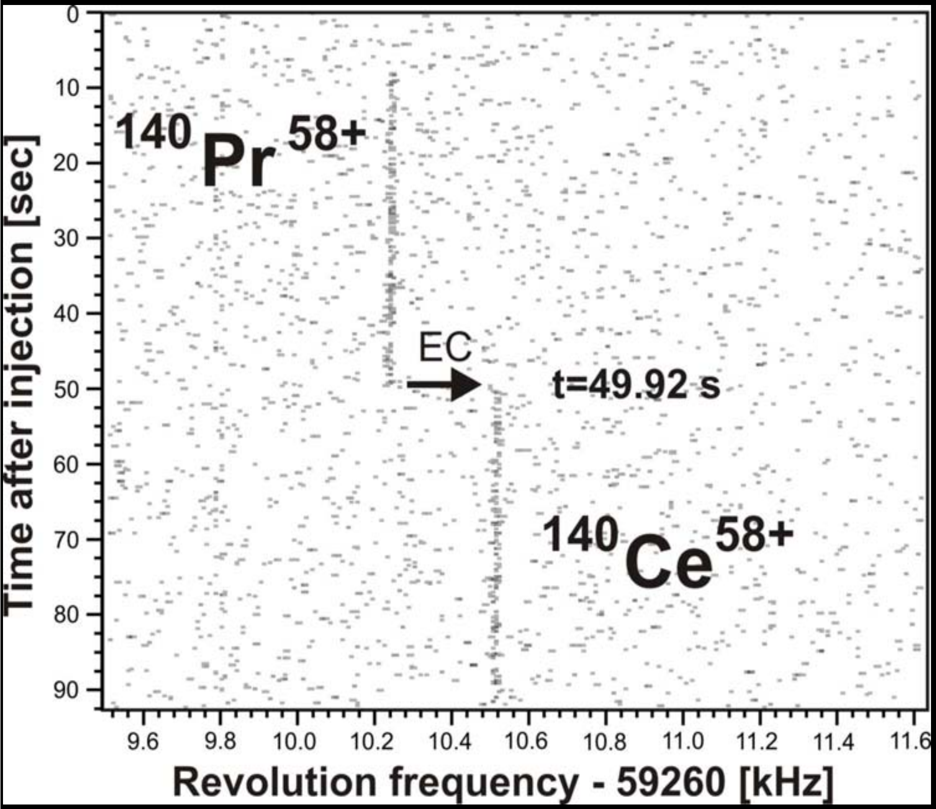


Time/channel = 30 sec.



$^{142}Pm^{1e^-}$
EC
t = 18.64 s
$^{142}Nd^{0e^-}$
β^+
t = 67.84 s
Time after injection into the ESR
Revolution frequency

2. Properties of the observed time ↔ frequency traces



1. Well-defined quantum states
2. Continuous observation
3. Parent/daughter correlation
4. Detection of all EC decays
5. Delay *d* between decay and "appearance" due to cooling:
6. Daughter nucleus and ν_e entangled by momentum and energy → EPR

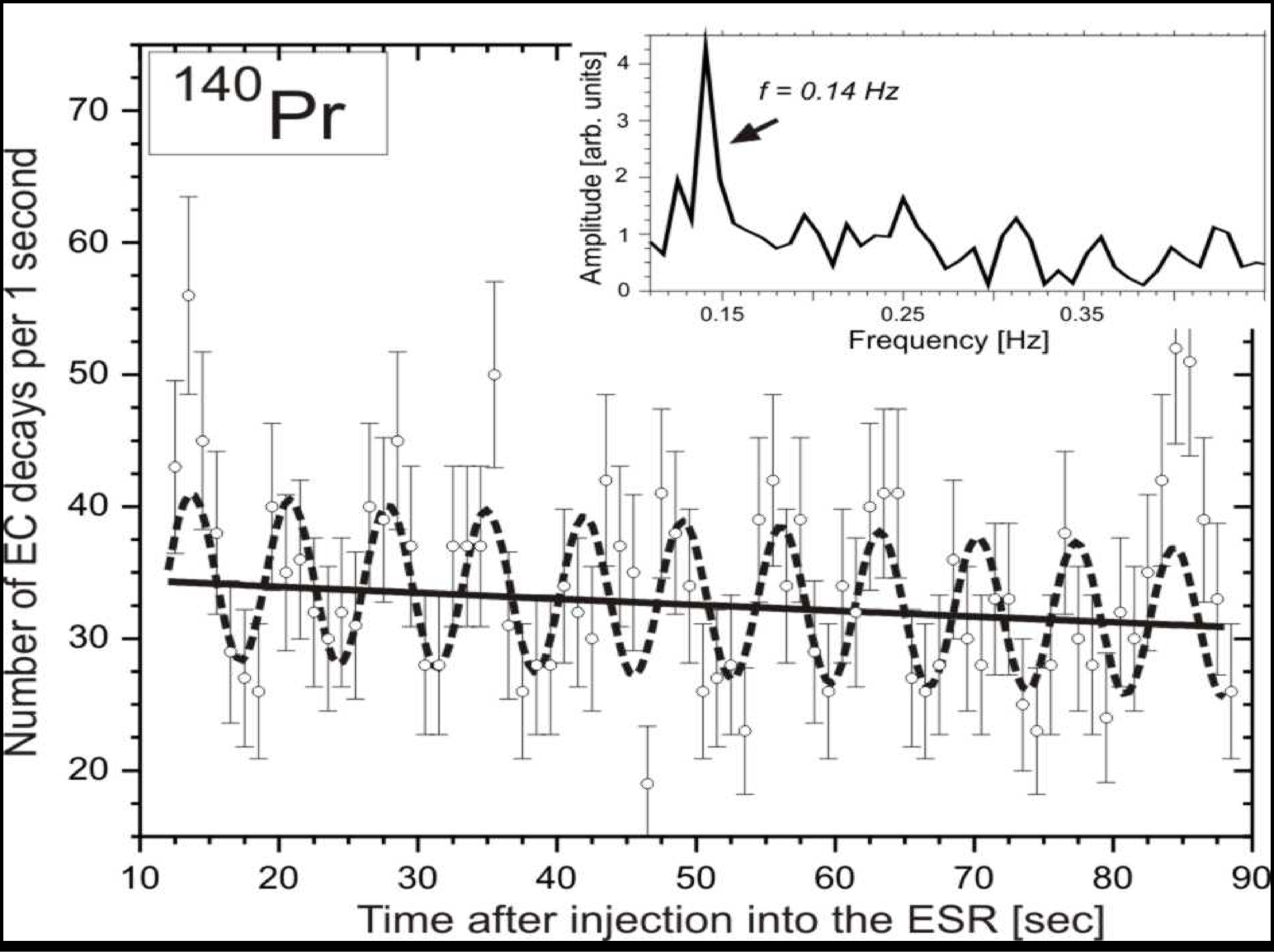
from measured frequency: → p transformed to n (hadronic vertex)

→ bound e^- annihilated (leptonic vertex)

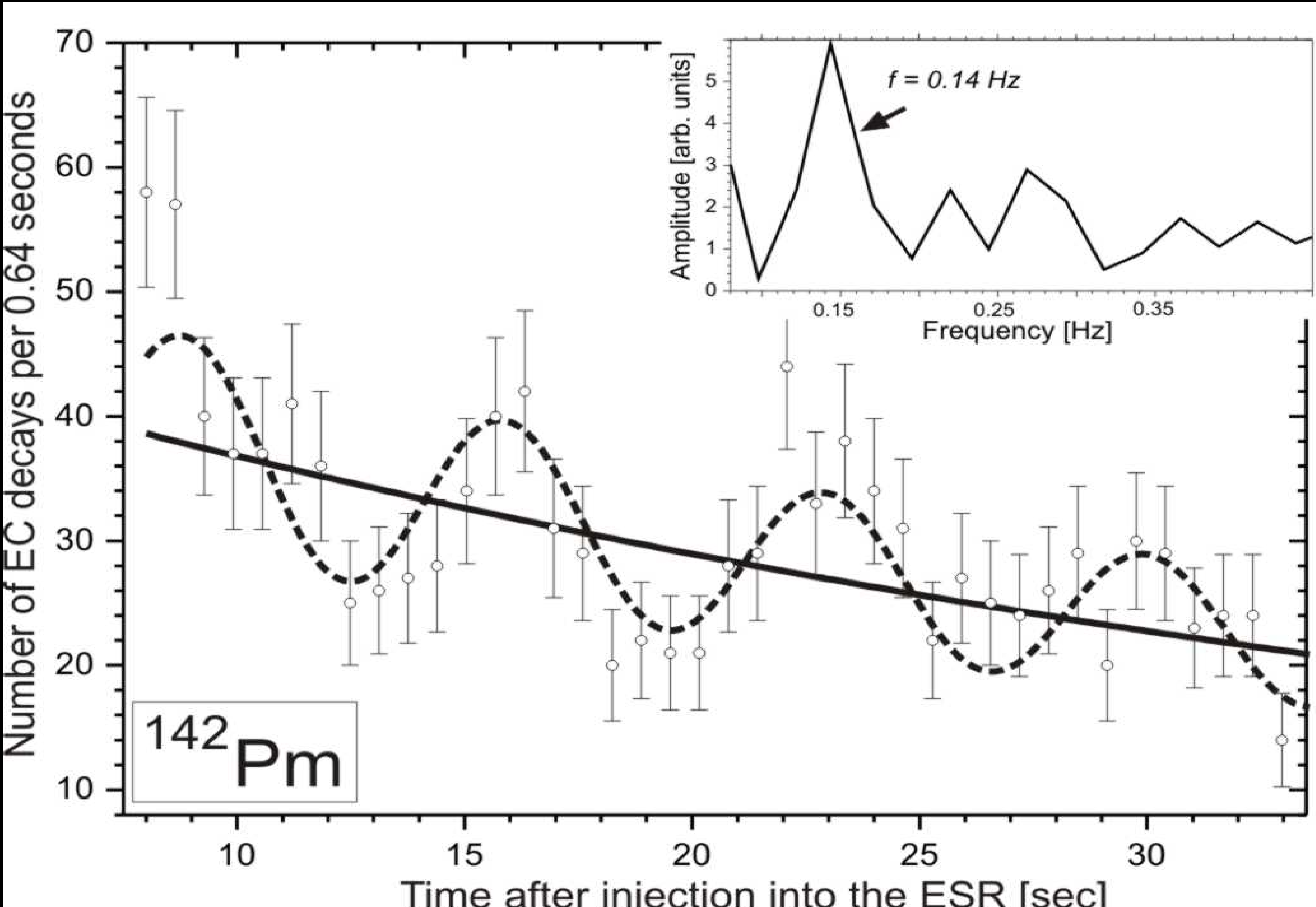
→ ν created at t_d as $\mathbf{\nu_e = a\,|\nu_1> + b\,\nu_2>}$

if conservation of lepton number holds

$^{140}Pr^{58+}$ 1.+2. run: **2650** EC-decays from 7102 injections



H-like $^{142}Pm^{60+}$: **2740 EC decays** from 7011 injections



2. A few out of many questions

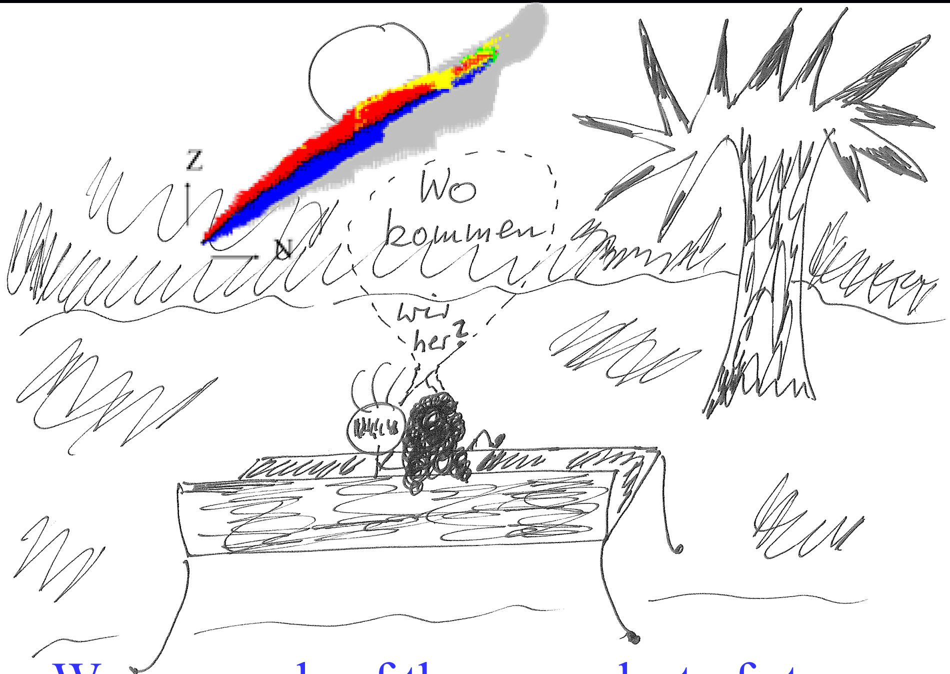
1. Are the modulations with a period of 7 seconds real ?
   → Artefacts nearly **excluded**, statistical significance only **3.5 σ**

2. Can the coherence be preserved over macroscopic times for a motion confined in an electromagnetic potential ?
   Do we have a real two-body decay ??

3. Do we 'reset' the clock (phase) by the continuous observation?

4. Do we observe a kind of 'quantum beats' due to the fact that the created **electron-neutrino is not a mass eigenstate ?**

Conclusion to be drawn - after all



...We are made of the same dust of stars as the earth, the moon, the sea and all other things are made of...

...Without the weak force neither the sun, the stars, nor ourselves would exist...

Honey, you' re right: I' ll put the **Karlsruhe Chart** into the **genealogical tree** of my upper-class family!

FRS / ESR Mass - and Lifetime - Collaboration

G. Audi, K. Beckert, P. Beller[†], F. Bosch, D. Boutin, C. Brandau, Th. Bürvenich, L. Chen, I. Cullen, Ch. Dimopoulou, H. Essel, B. Fabian, Th. Faestermann, B. Franczak, B. Franzke, H. Geissel, E. Haettner, M. Hausmann, S. Hess, P. Kienle, O. Klepper, H.-J. Kluge, Ch. Kozhuharov, R. Knöbel, J. Kurcewicz, S.A. Litvinov, Yu.A. Litvinov, Z. Liu, L. Maier, M. Mazzocco, F. Montes, A.Musumarra, G. Münzenberg, S. Nakajima, C. Nociforo, F. Nolden, Yu.N. Novikov, T.Ohtsubo, A. Ozawa, Z. Patyk, B. Pfeiffer, W.R. Plass, Z. Podolyak, M. Portillo, A. Prochazka, R. Reuschl, H. Schatz, Ch. Scheidenberger, M. Shindo, V. Shishkin, U. Spillmann, M. Steck, Th. Stöhlker, K. Sümmerer, B. Sun, K. Suzuki, K. Takahashi, S. Torilov, M.B.Trzhaskovskaya, S.Typel, D.J. Vieira, G.Vorobjev, P.M. Walker, H. Weick, S. Williams, M. Winkler, N. Winckler, D. Winters, H. Wollnik, T. Yamaguchi

Classical quantum beats vs.EC-decay in the ESR

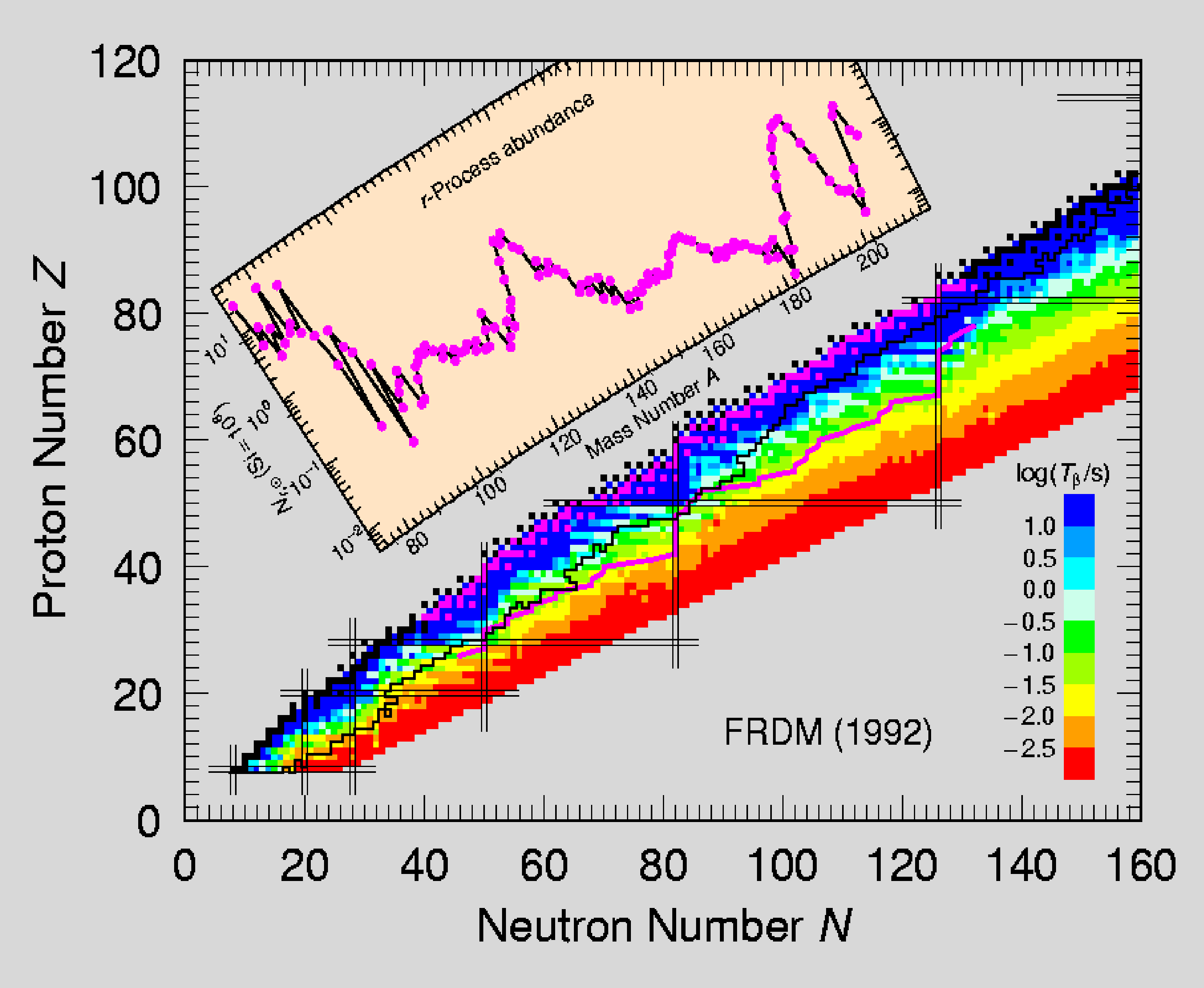
Quantum beats

- **two** well-defined initial states
- excited atom moves **free** in space
- observation time **nanoseconds** - microseconds

EC - decay of H-like ions stored in a ring

- parent atom created by **nuclear reaction**
- moves **confined** by electromagnetic forces
- interacts with e^- of the cooler, atoms, beam pipe..
- observation time some **10 seconds**

1. The deep entanglement of nuclear structure and stellar nucleosynthesis



Beats due to neutrino being not a mass eigenstate?

A few out of many objections :

1. No coherence due to the orthogonality of mass eigenstates

C. Giunti, arXiv: 0801.4639v1 [hep-ph], January 30, 2008

$$|\nu_e(t_d)> = \Sigma A_k(t_d)\,|\nu_k(t_d)> \quad \text{(eq. 9)}$$

$\rightarrow$ decay amplitude $\mathbf{A(t_d)} = (\Sigma\,|\alpha_k A_k(t_d)\,|\nu_k(t_d)>|^2)^{1/2}$

One has to **project** $|\nu(t_d)>$ onto the flavour eigenstate $|\nu_e>$ at the moment t_d of the **"real" emission** of the neutrino(s)

$$|\nu(t_d)> = \Sigma A_k(t_d)\,|\nu_e><\nu_e|\nu_k(t_d)>$$

$\rightarrow$ decay amplitude $\mathbf{A(t_d)} = (|\Sigma\,\alpha_k A_k(t_d)\,|\nu_k(t_d)>|^2)^{1/2}$

Beats due to neutrino being **not** a mass eigenstate?

1. We do'nt observe the neutrino:→ **no** interference (H.Feldmeier)

2. Beats are only possible if the **flavour** is determined at both the **generation and the decay** (M. Lindner)

3. One observes the quantum state of the system **continuously** :
   → **no beats** (C. Giunti, arXiv: 0801.4639V2),
   except the two states **cannot** be distinguished (C. Giunti V3)

EC in H-like ions for nuclear g.s. → g.s. transitions

Decay identified by **correlated change** of atomic mass at time t_d

Different **delay** due to emission characteristics of the neutrino

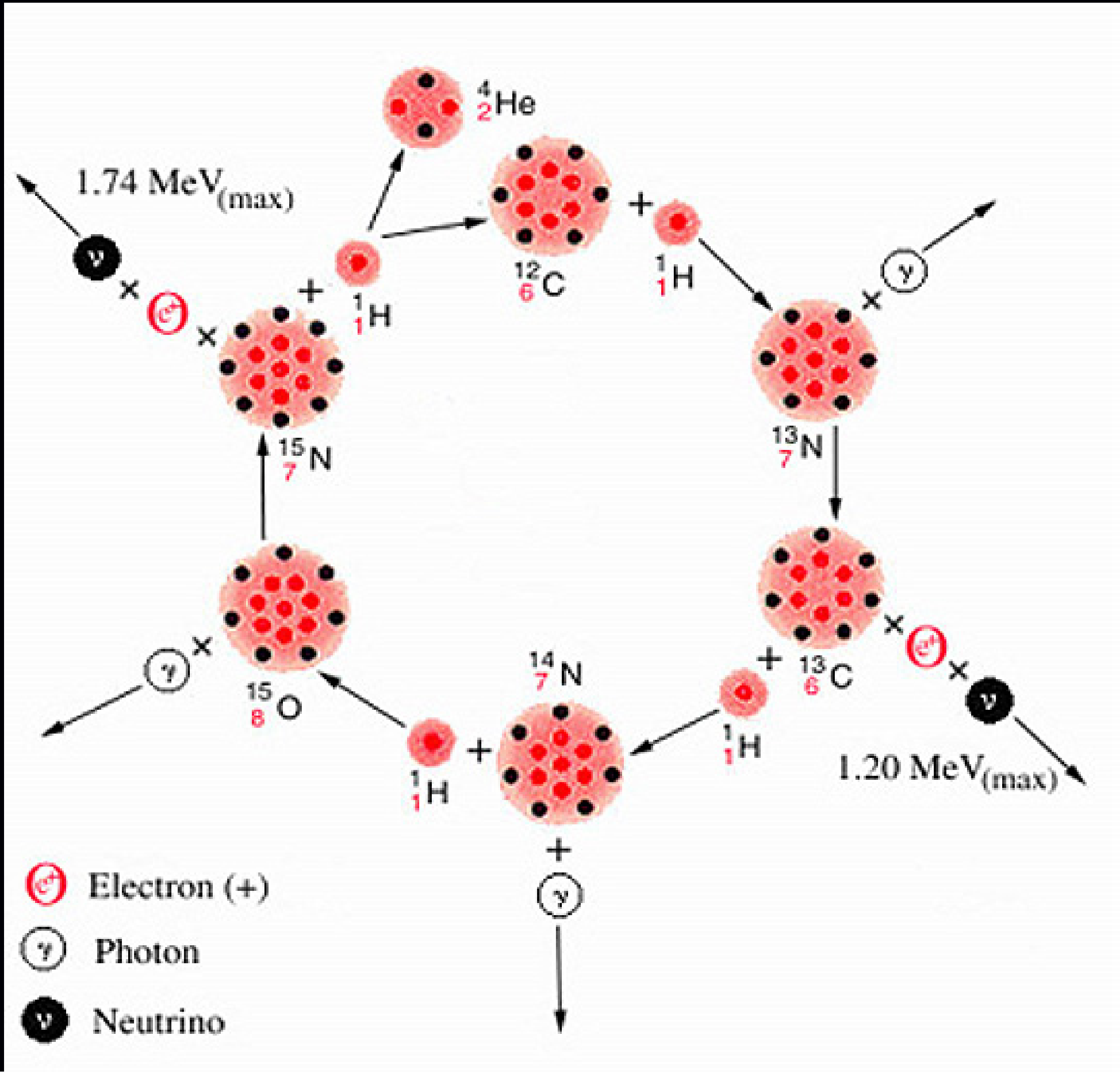
Small total line width(s)

$\hbar / \Delta t_{Obs}$ (≈ 0.1 s) ≈ 10^{-14} eV >> $\hbar / T$ (≈ 7 s) ≈ 10^{-16} eV

No third particle involved

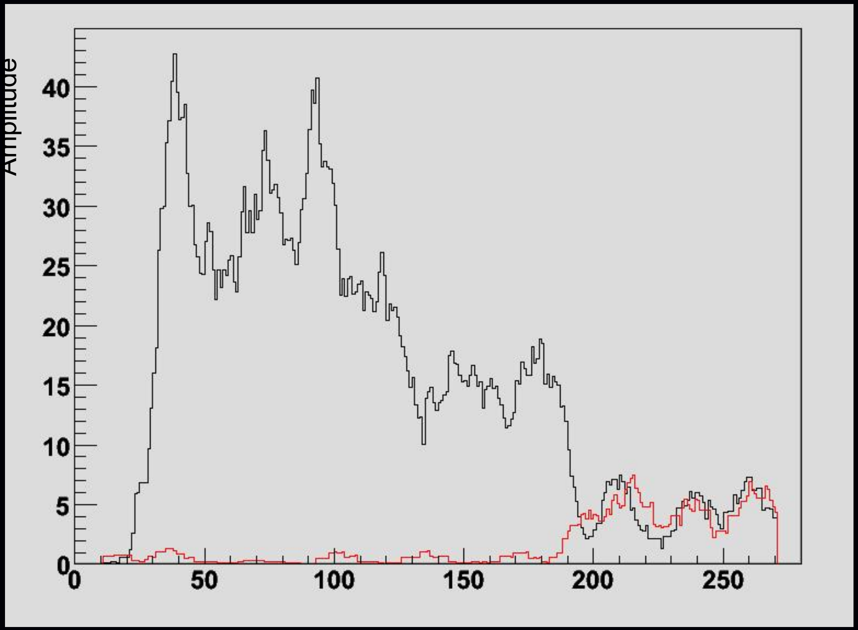
→ daughter nucleus and neutrino **entangled** by momentum- and energy conservation → **EPR** scenario

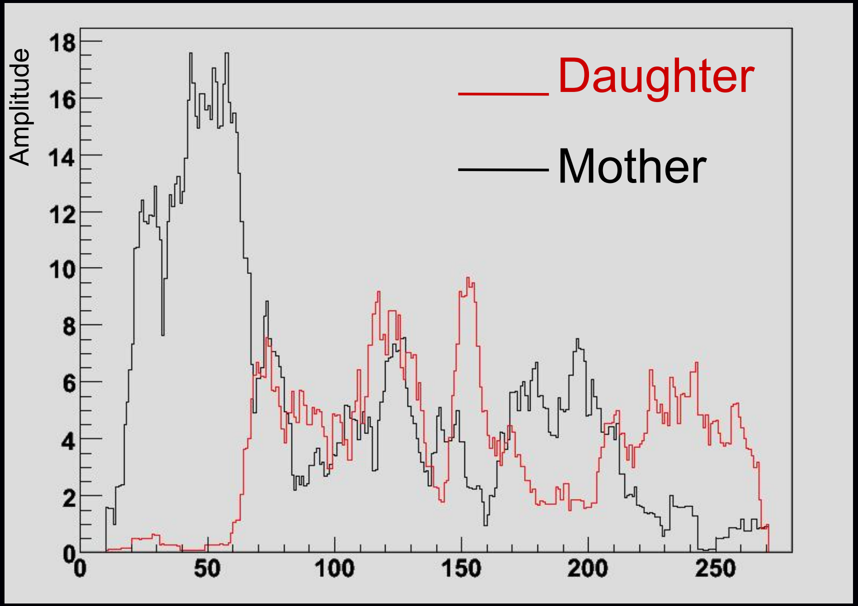
1. β decay and stellar nucleosynthesis: CNO-cycle



Why we have to restrict onto 3 injected ions at maximum ?

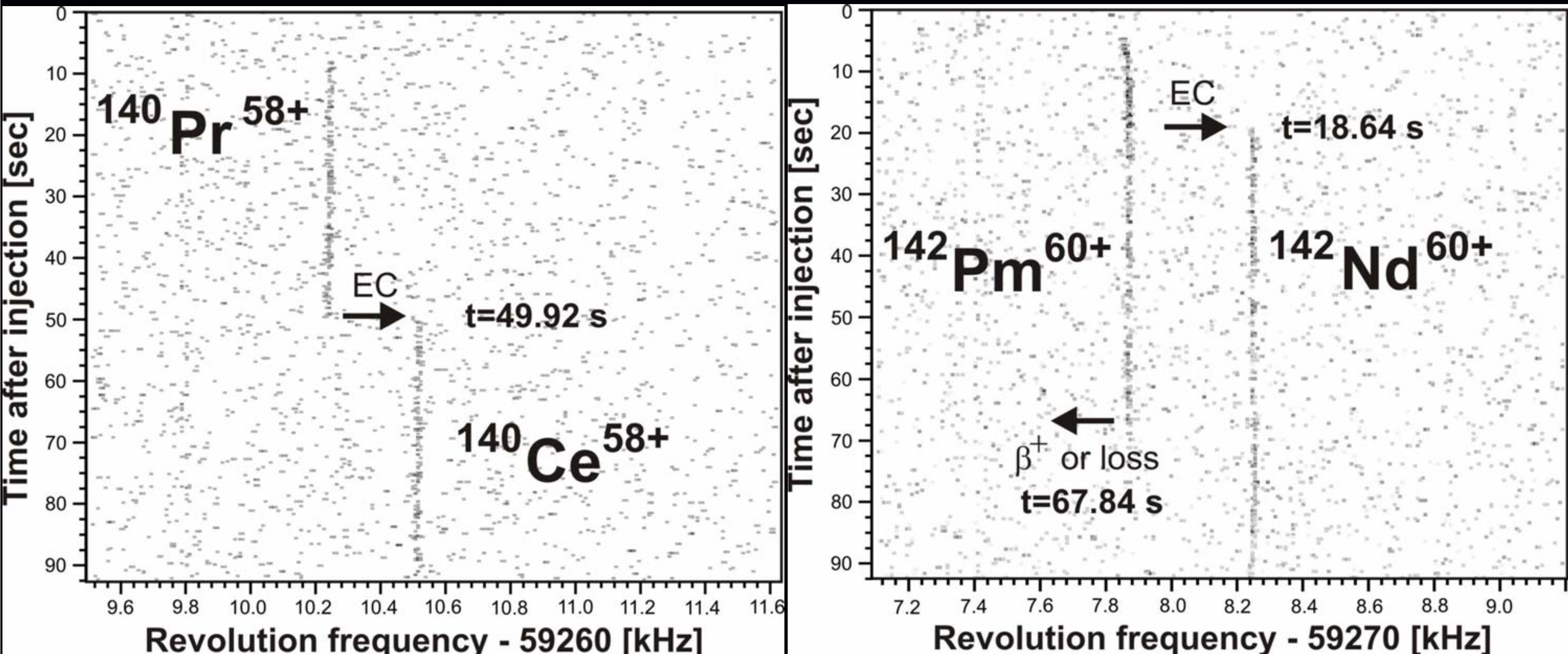
The variance of the amplitude gets larger than the step 3→4 ions





evaluation of amplitude distributions
corresponding to **1,2,3-particles**

Examples of measured time-frequency traces



1. Continuous observation
2. Parent/daughter correlation
3. Detection of all EC decays
4. Delay between decay and "appearance" due to cooling

"Classical" quantum beats

Coherent excitation of an electron in two quantum states, separated by ΔE at time t_0, e.g. $^3P_0$ and $^3P_2$

Observation of the decay photon(s) as a function of $(t-t_0)$

Exponential decay modulated by

$$\cos(\Delta E/h\ 2\pi\ (t-t_0))$$

if $\Delta T \ll \Delta t = h/(2\pi\Delta E)$

→ no information whether E_1 or E_2

"which path"? addition of **amplitudes**

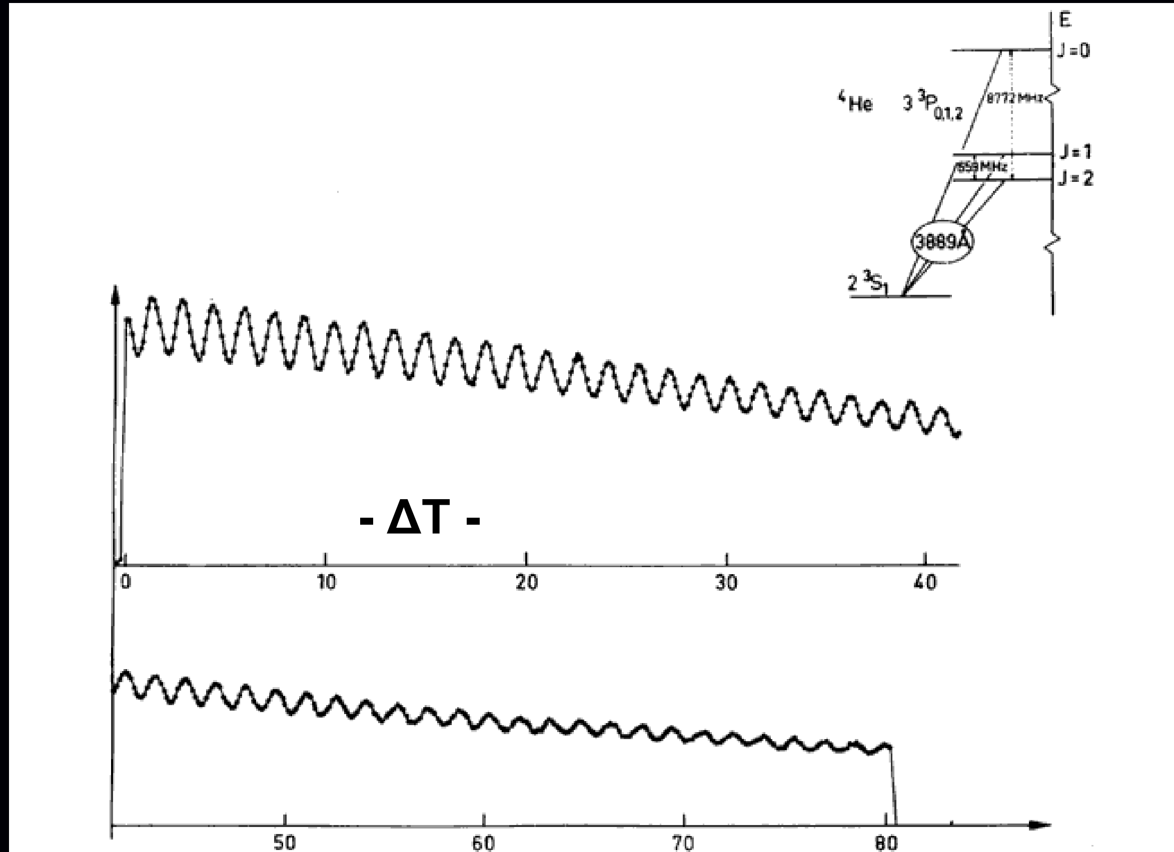


Fig. 24. Zero-field oscillations between the 1s 3p $^3P_1$ and 1s 3p $^3P_2$ states in He I (659 MHz), Wittmann [248]. The oscillations are superimposed on the exponential decay of the 1s 3p ^3P term (96 ns). To record this decay curve about 10 hours beam time (a few μA) and more than 20 carbon foils were needed.

Chow et al., PR **A11**(1975) 1380

Periodic transfer from F = 1/2 to "sterile" F = 3/2 ?

- 1. Decay constants for H-like ^{140}Pr and ^{142}Pm should get smaller than expected. ⟶ NO
- 2. Statistical population in these states after
- $t \approx \max [1/\lambda_{flip}, 1/\lambda_{dec.}]$
-
- 3. Phase matching over many days of beam time?

Quantum beats vs. EC-decay in the ESR

- **Quantum beats**
- - two well-defined initial states
- - excited atom moves free in space
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- **EC - decay of H-like ions stored in a ring**
- - parent atom created by nuclear reaction
- - moves confined by electromagnetic forces
- - interacts with e^- of the cooler, atoms, beam pipe..
- - observation time some 10 seconds

arXiv.org > nucl-th > arXiv:0811.2302v1

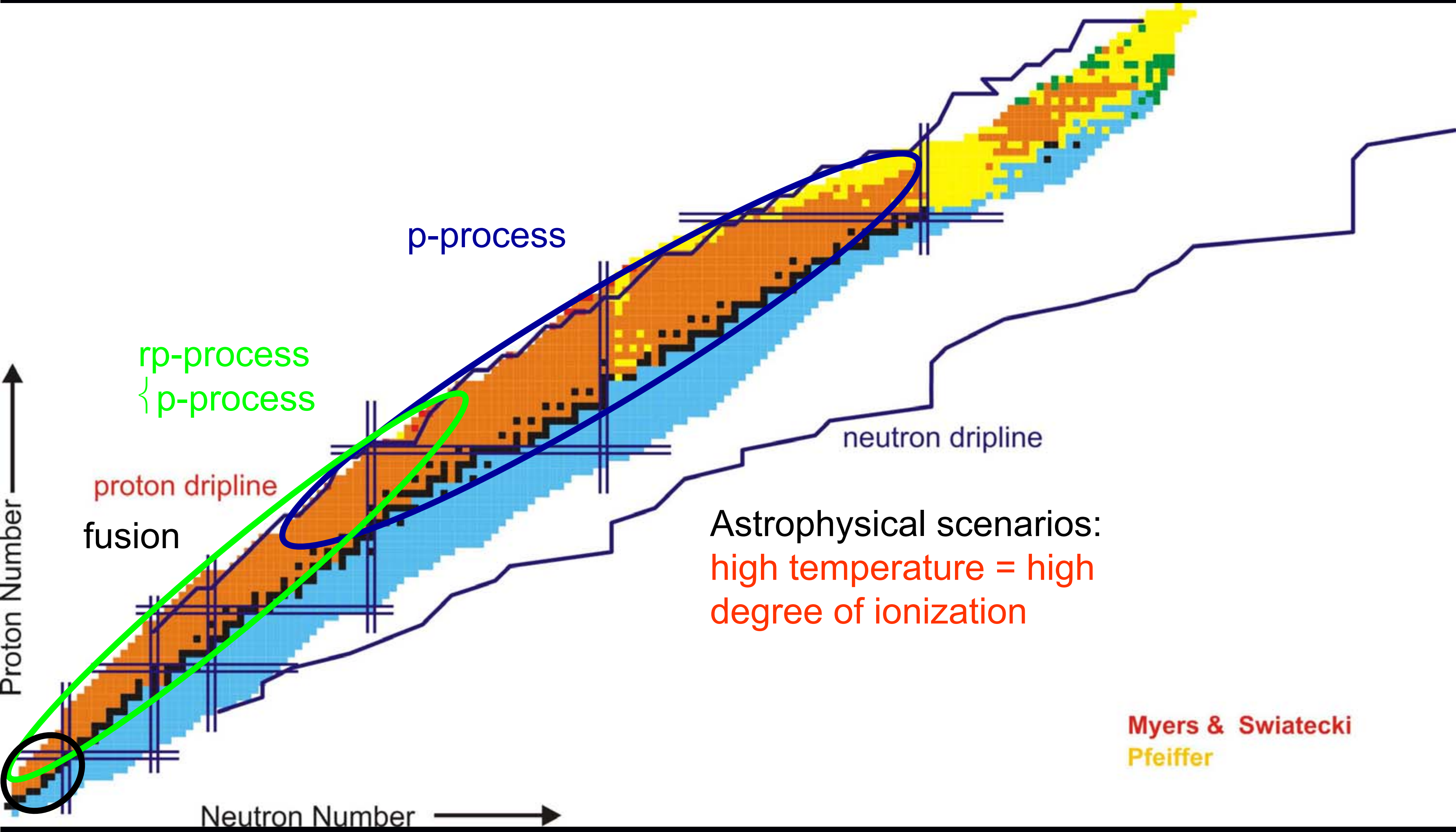
Spin-rotation coupling in non-exponential decay of hydrogen-like heavy ions

G. Lambiase, G. Papini, G. Scarpetta

(Submitted on 14 Nov 2008)

We discuss a model in which a recently reported modulation in the decay of the hydrogen-like ions $^{140}Pr^{58+}$ and $^{142}Pm^{60+}$ arises from the coupling of rotation to the spin of electron and nuclei (Thomas precession). A similar model describes the electron modulation in muon g-2 experiments correctly. Agreement with the GSI experimental results is obtained for the current QED-values of the bound electron g-factors, g($^{140}Pr^{58+}$)=1.872 and $^{142}Pm^{60+}$=1.864, if the Lorentz factor of the bound electron is about 1.88. The latter is fixed by either of the two sets of experimental data. The model predicts that the modulation is not observable if the motion of the ions is linear, or if the ions are stopped in a target.

Beta-Decays on the Chart of Nuclides



Astrophysical scenarios:
high temperature = high degree of ionization

Landscape of precisely measured masses at GSI

Masses of more than 1100 Nuclides were measured

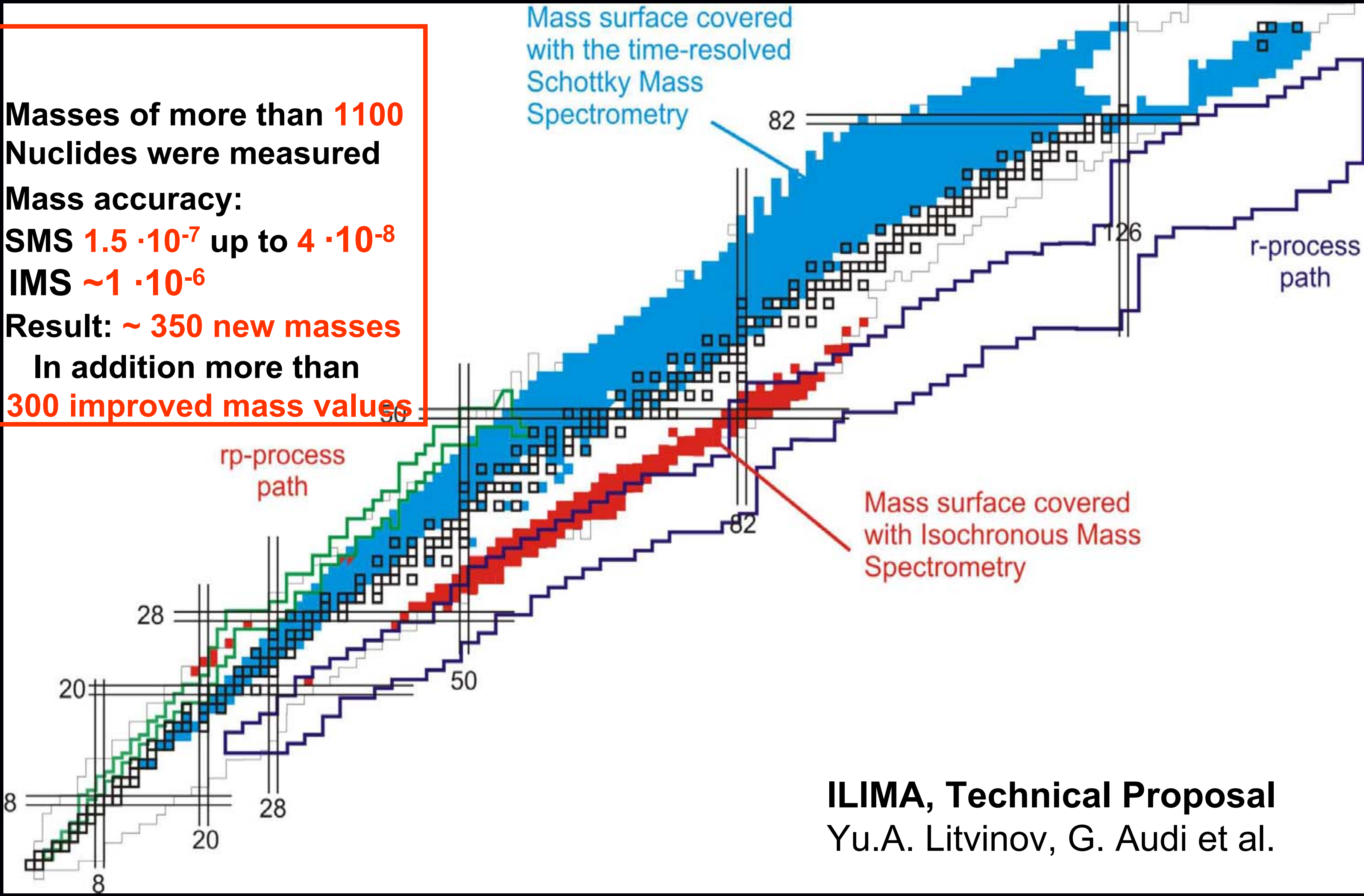
Mass accuracy:

SMS $1.5 \cdot 10^{-7}$ up to $4 \cdot 10^{-8}$

IMS $\sim 1 \cdot 10^{-6}$

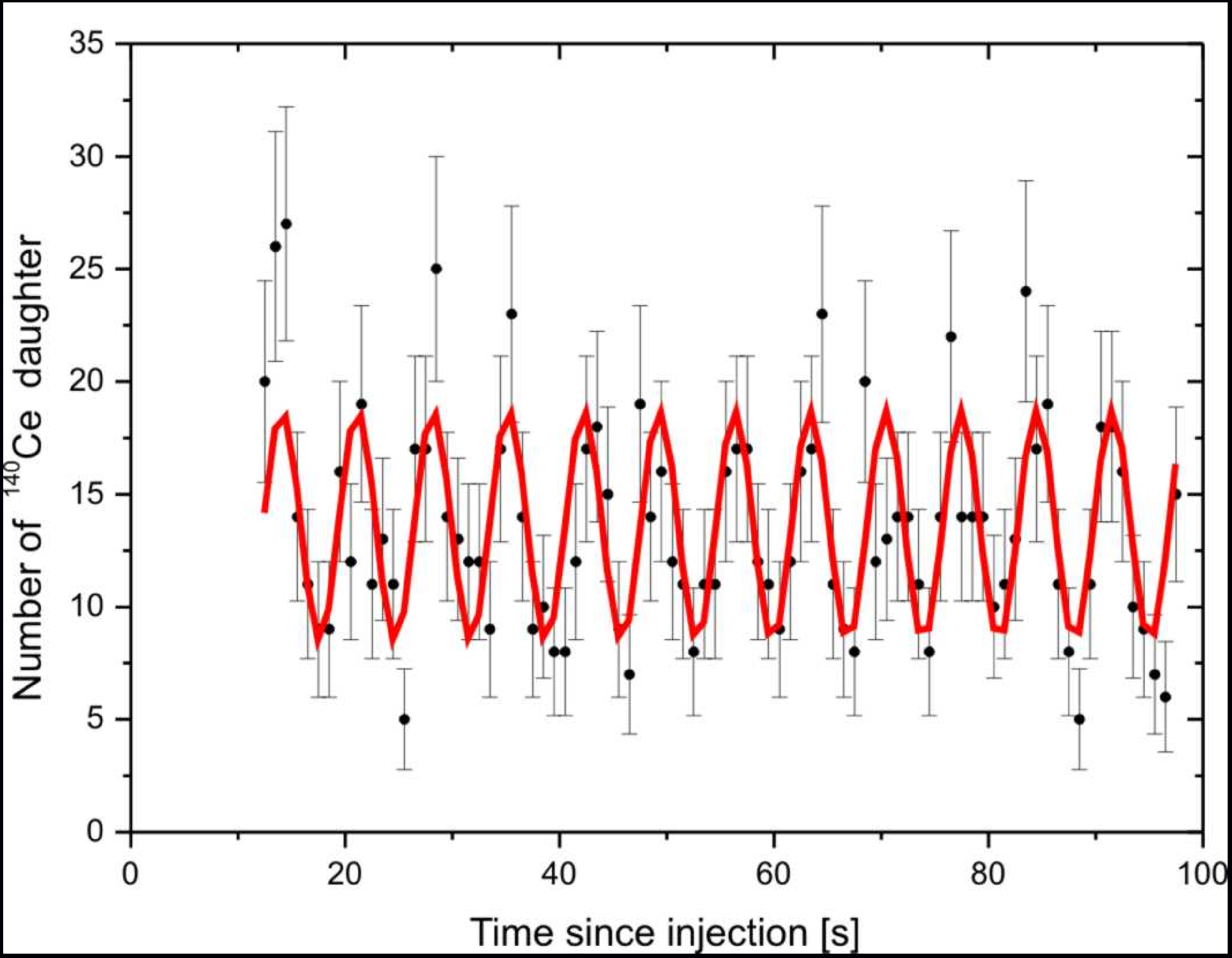
Result: ~ 350 new masses

In addition more than 300 improved mass values



ILIMA, Technical Proposal
Yu.A. Litvinov, G. Audi et al.

2. Results: Number of EC decays of H-like $^{140}Pr^{58+}$ / s in the **1. run**



- 2. Fit results: pure exponential (1); superimposed oscillation (2)

- $dN_{EC}(t)/dt = N_0 \exp\{-\lambda t\}\, \lambda_{EC}$; $\lambda = \lambda_{\beta+} + \lambda_{EC} + \lambda_{loss}$ (1)

- $dN_{EC}(t)/dt = N_0 \exp\{-\lambda t\}\, \lambda_{EC}(t)$; $\lambda_{EC}(t) = \lambda_{EC}\,[1 + a\cos(\omega t + \varphi)]$ (2)

Fit parameters of ^{140}Pr data					
Eq.	$N_0\lambda_{EC}$	λ	a	ω	χ^2/DoF
1	34.9(18)	0.00138(10)	-	-	107.2/73
2	35.4(18)	0.00147(10)	0.18(3)	0.89(1)	67.18/70

T = 7.06 (8) s
φ = 0.4 (4)
a = 0.18 (3)

Fit parameters of ^{142}Pm data					
Eq.	$N_0\lambda_{EC}$	λ	a	ω	χ^2/DoF
1	46.8(40)	0.0240(42)	-	-	63.77/38
2	46.0(39)	0.0224(41)	0.23(4)	0.89(3)	31.82/35

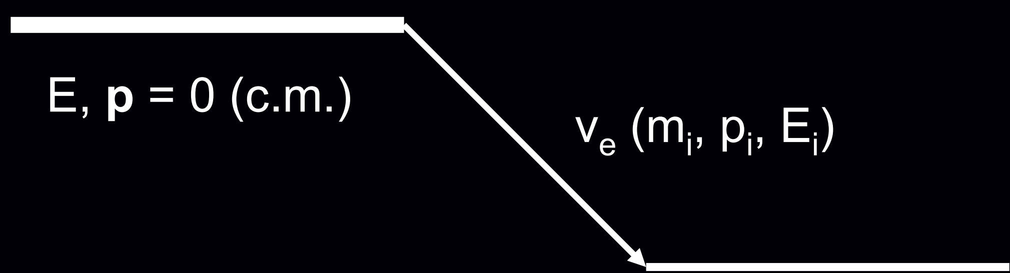
T = 7.10 (22) s
φ = - 1.6 (4)
a = 0.23 (4)

Beats due to neutrino being not a mass eigenstate?

The electron neutrino appears as coherent superposition of mass eigenstates

$$|\nu_e\rangle = \cos\theta\, |\nu_1\rangle + \sin\theta\, |\nu_2\rangle$$

The **recoils** appear as coherent superpositions of states **entangled** with the electron neutrino mass eigenstates by momentum- and energy conservation



$M + p_1^2/2M + E_1 = E$

$M + p_2^2/2M + E_2 = E$

"Asymptotic" conservation of E, **p**

$$E_i^2 = p_i^2 + m_i^2$$

$$m_1^2 - m_2^2 = \Delta^2 m = 8 \cdot 10^{-5}\ \mathrm{eV}^2$$

$$E_1 - E_2 = \Delta E_\nu$$

$$\Delta E_\nu \approx \Delta^2 m / 2M \qquad = 3.1 \cdot 10^{-16}\ \mathrm{eV}$$

$$\Delta p_\nu \approx -\Delta^2 m / 2 \langle p_\nu \rangle = 2.0 \cdot 10^{-11}\ \mathrm{eV}$$

- **cos ($\Delta E/\hbar\ t$) with $T_{lab} = h\ \gamma\ /\ \Delta E \approx$ 7s**

- a) M = 140 amu, E_ν = 3.39 MeV (Pr)
- b) M = 142 amu, E_ν = 4.87 MeV (Pm)

- M =141 amu, γ = 1.43, $\Delta^2 m_{12} = 8 \cdot 10^{-5}\ eV^2$

- **$\Delta E = h\gamma\ /\ T_{lab} = 8.4 \cdot 10^{-16}$ eV**
- **$\Delta E_\nu = \Delta^2 m\ /2\ M = 3.1 \cdot 10^{-16}$**

Can data of **stored** and **implanted** ions be compared?

P.A. Vetter et al (2008): Implantation of ^{142}Pm in a lattice

arXiv: 0807.0649 (PLB) Observation of K x-rays of daughter:

→ pure exponential decay observed

T. Faestermann et al (2008): Implantation of ^{180}Re into a lattice:

arXiv:0807.3651 (PLB) Observation of γ rays of daughter

→ pure exponential decay observed

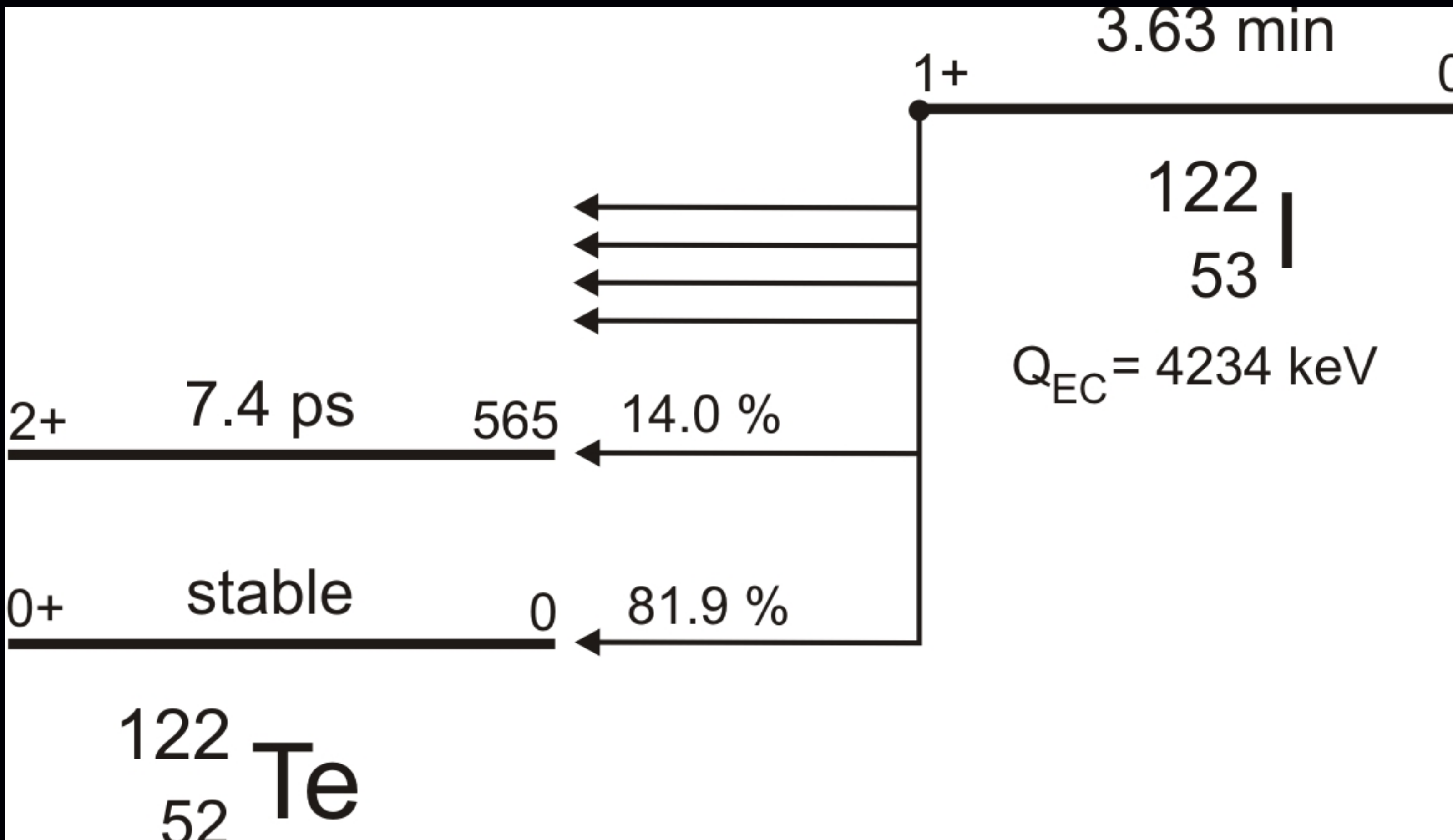
- For the two-body EC decays of H-like ^{140}Pr and ^{142}Pm periodic modulations according to $e^{-\lambda t}[1+a\cos(\omega t+\varphi)]$
  - with $T_{lab} = 2\pi/\omega = 7s$, $a \approx 0.20$ were found

- Statistical fluctuations are not excluded on a c.l. > 3.5 σ

- Supposing $\Delta E = h\,\gamma/T_{lab} = \Delta^2 m_{12} / 2M$ ($\gamma = 1.43$)
  - $\rightarrow \Delta^2 m_{12} = (2M\,h\,\gamma) / T_{lab} = 2.20 \cdot 10^{-4}\ eV^2$

- Things will become really interesting only if
  - oscillations would be observed for other
  - two-body beta decays with different periods
  - (proportional to nuclear mass ??)

Decay scheme of ^{122}I – Experiment in August 2008



Decay statistics

Correlations: 10.808 injections ~1080 EC-decays
Many ions: 5718 injections ~5000 EC-decays

Analyzed :
I. About 60% of the overall data
II. About 20% of the overall data
Automatic analysis is delayed

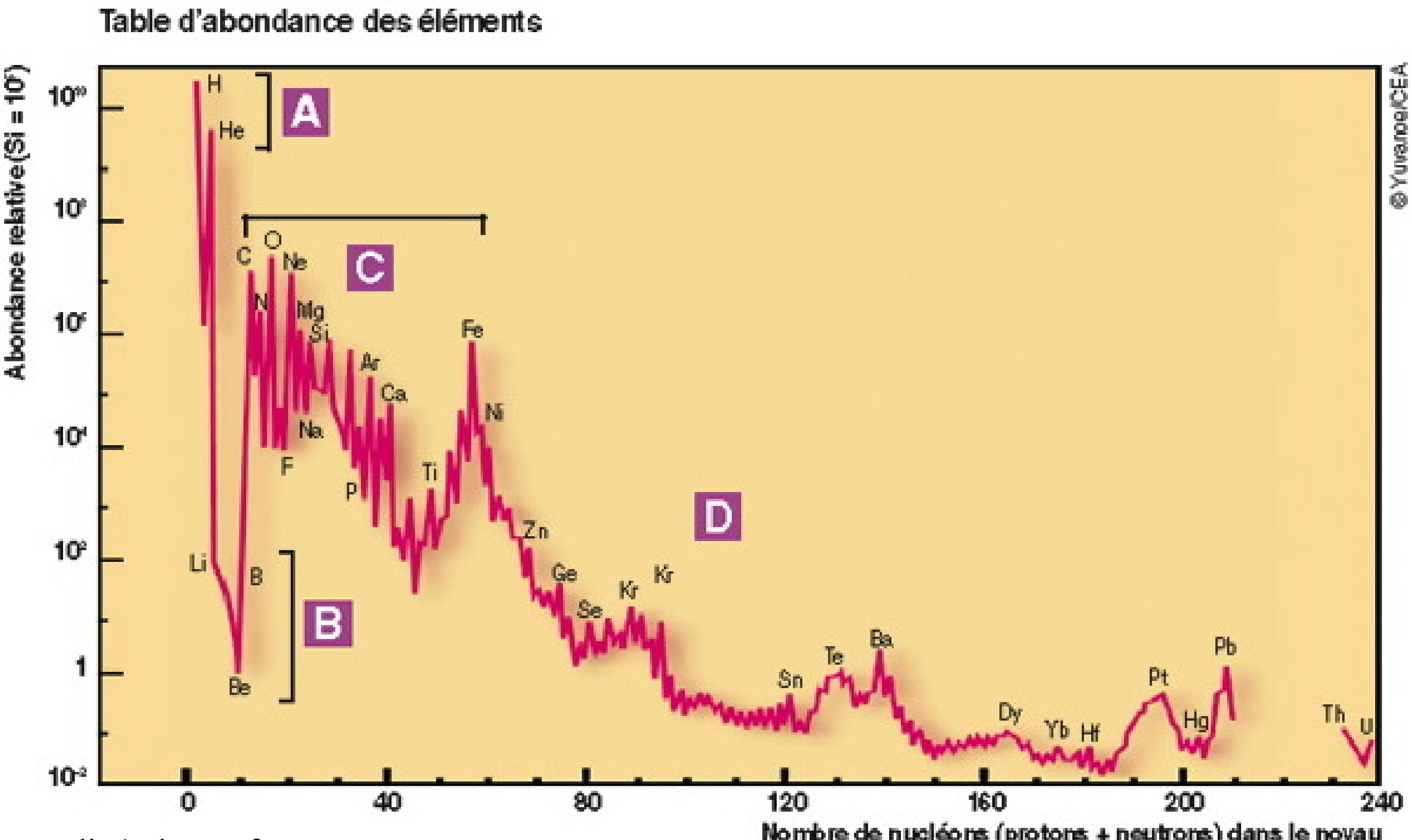
1. β decay and stellar nucleosynthesis: s-, rp-, r- process

s- process: interplay of **slow neutron capture and β^- decay**
near the valley of stability. Site: supergiant stars

r- process: interplay of **rapid neutron capture and β^- decay**
site: perhaps exploding supernova II (?)

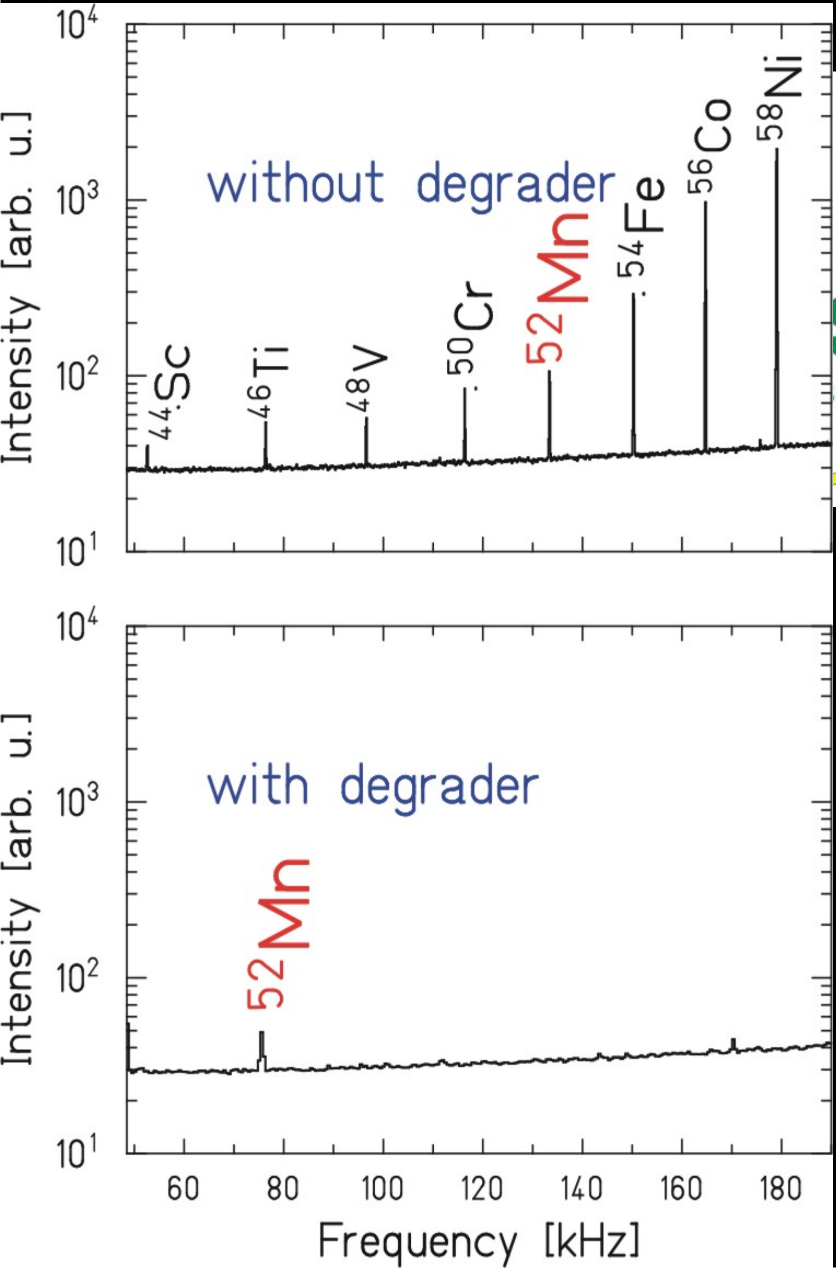
rp- process: interplay of **rapid proton capture and β^+ decay**
site: binary system (white dwarf and red giant)
onset of explosive H-burning by accreting mass

...understanding finally the relative abundances of all nuclides in our solar system and anywhere else



media4.obspm.fr

2. Production and Separation of exotic nuclides



Highly-Charged Ions

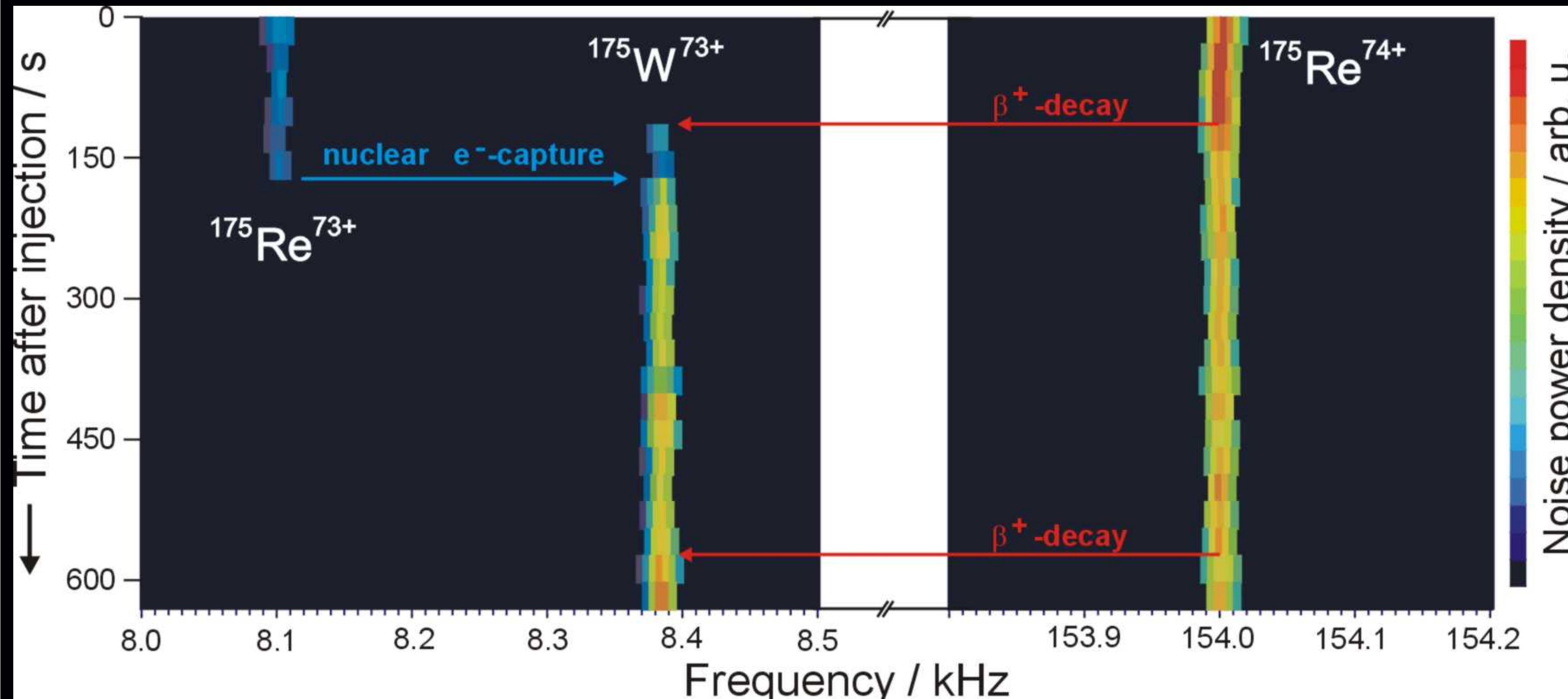
In-Flight **separation**

Cocktail or one single nuclear species

600 MeV/u primary beams

400 MeV/u stored beams = 0.7 c

2. Three- and two-body β decay of single stored and cooled ions



Time/channel = 30 sec.

H-like $^{142}Pm^{60+}$: **2740** EC decays from 7011 njections